GEOLOGICAL SURVEY CIRCULAR 129

HYDROLOGIC RECONNAISSANCE OF THE GREEN RIVER IN UTAH AND COLORADO

By H. E. Thomas

UNITED STATES DEPARTMENT OF THE INTERIOR
Oscar L. Chapman, Secretary

GEOLOGICAL SURVEY
W. E. Wrather, Director

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ABSTRACT

The Green River, rising in Wyoming and draining high mountains in that state, northeast Utah and northwest Colorado, is a major tributary of the Colorado River. In the late summer, after the snow has melted from these mountains, the flow in the Green River reaches its minimum for the year. At that time a large proportion of the water in the river is returned to the atmosphere by evaporation and transpiration.

During a 21-day period in September 1948, when the flow was least for the year, the average flow of the river as it entered Utah from Wyoming was 515 cfs. In the 437 miles of its course through Utah and Colorado evapotranspiration losses averaged 430 cfs. The average discharge of the Green River into the Colorado was about 975 cfs. Contributions to the river in Utah and Colorado totalled 890 cfs, including 560 from tributaries. The calculated ground-water inflow was about 330 cfs, of which about 75 percent was contributed within the Uinta Basin. Very little ground water was contributed to the river in the lower 180 miles of its course, where the river flows through canyon lands of the Colorado Plateaus.

These estimates are based upon information collected during a boat reconnaissance in September 1948, and upon data available from stream-gaging stations along the Green River and many of its tributaries. From these data an accounting was made of the water--as to both quantity and quality--in several segments of the river. For each segment determinations were made of the surface outflow, loss by evapotranspiration, and surface- and ground-water inflow. During the reconnaissance information was also obtained as to the relation of stream flow to regional geology and ground-water hydrology.

No detailed hydrologic studies have yet been made within the drainage basin of the Green River. On the basis of this reconnaissance, detailed studies in the Uinta Basin, Browns Park, and Echo Park areas are recommended as highly desirable, because of the possible relations of ground-water hydrology to river-basin development projects. Similar reconnaissance can be of value in delineating the areas where detailed hydrologic studies would be most fruitful throughout the upper Colorado River basin.

INTRODUCTION

Need for basic hydrologic data

The upper basin of the Colorado River system has been defined as the drainage area above Lee Ferry, Ariz., which is about a mile below the mouth of the Paria River. (Lee Ferry is below the mouth of the Paria River; Lees Ferry is above.) The drainage area of 110,000 sq mi includes parts of the States of Arizona, Colorado, New Mexico, Utah, and Wyoming. This upper basin has an extensive but still inadequate network of precipitation and stream-gaging stations, and its water resources have been summarized in reports by LaRue (1925), Follansbee (1929), and Wooley (1930). Detailed studies to show the occurrence of ground water and its relation to stream flow, the natural discharge of water by evapotranspiration, the water-bearing properties of the rocks of the basin, and the relation of the rock strata to the dissolved minerals and suspended sediment in the streams, have not been made for any part of the upper basin.

The compacts and treaties in operation prior to 1948 required little hydrologic information on the upper basin. The Colorado River Compact of November 24, 1922, which apportions the water between the upper and lower basins, requires the determination of the outflow from the upper basin, and this is computed from the records of the gaging stations on the Colorado River at Lees Ferry and on the Paria River at the mouth. The treaty between the United States of America and the United Mexican States, dated February 3, 1944 (Treaty Series 994), can be administered with no data from the upper basin except the quantity of water passing Lee Ferry, determined by the same two gaging stations. Compacts concerning the apportionment of the waters of certain tributaries, such as the LaPlata River Compact of November 27, 1922, have required the operation of some gaging stations on those tributaries, but no data on the upper basin as a whole.

Far more basic hydrologic data will be required for administration of the Upper Colorado River basin Compact of October 11, 1948. The basis for apportionment of water is contained in Article III of the Compact, which reads in part:

(a) Subject to the provisions and limitations contained in the Colorado River Compact and in this Compact, there is hereby apportioned from the Upper Colorado River System in perpetuity to the States of Arizona, Colorado, New Mexico, Utah and Wyoming, respectively, the consumptive use of water as follows:

(1) To the State of Arizona the consumptive use of 50,000 acre-feet of water per annum.

(2) To the States of Colorado, New Mexico, Utah and Wyoming, respectively, the consumptive use per annum of the quantities resulting from the application of the following percentages of the total quantity of consumptive use per annum apportioned in perpetuity to and available for use each year by Upper Basin under the Colorado River Compact and remaining after the deduction of the use, not to exceed 50,000 acre-feet per annum, made in the State of Arizona.

State of Colorado.......51.75%
State of New Mexico.....11.25%
State of Utah...........23.00%
State of Wyoming........14.00%

Article VI of the Compact specifies that "The Upper Colorado River Commission shall determine the quantity of the consumptive use of water, which use is apportioned by Article III hereof, for the Upper Basin and for each State of the Upper Basin by the inflow-outflow method in terms of man-made depletions of the virgin flow at Lee Ferry, unless the Commission, by unanimous action, shall adopt a different method of determination."

It is evident that proper apportionment of the water in accordance with this Compact will require information as complete as possible concerning the quantities of water, both surface and subsurface, that cross State boundaries, and the relation of those quantities to the flow in the Colorado River at Lee Ferry. With respect to each project for development of the water resources in the upper basin, the Compact requires a determination of the "quantity of consumptive use of water...in terms of man-made depletions of the virgin flow at Lee Ferry," a determination that requires knowledge of the quantities diverted for the project and the quantities returned to the stream, as well as the difference between natural losses before and after the project begins operation. Inasmuch as the consumptive (beneficial) use of water by each State is calculated in relation to its depletion of the virgin flow at Lee Ferry, it becomes essential to know the extent of the natural losses from the river, before these virgin-flow conditions are changed by the development of projects. The regional hydrology should be known in sufficient detail at each prospective reservoir site to assure the States that these reservoirs are not located where the geologic structure is favorable for large leakage of water into permeable but unsaturated strata.

Scope and purpose of reconnaissances of main-stem canyons

In so large an area as the upper Colorado River basin, complete information regarding sources and movements of water, measurement of water crossing State boundaries, and determination of natural losses from the river system will require large expenditures and a large corps of hydrologists. It is likely, however, that investigation of the main stems of the Colorado and its principal tributaries will show that some parts of the drainage basin make negligible contributions to the stream flow, and that study of those areas can be deferred. In Utah those main stems are in deep canyons throughout most of their courses, and not easily accessible for study. The best methods of coverage of the entire course of the river is by boat, but because of numerous rapids the trip is only slightly less hazardous than when Powell first made it in 1869.

This paper presents data obtained during boat reconnaissance of the Green River south of the Wyoming State line (fig. 1). Some of the information obtained during these trips, for instance the data concerning the relation of stream flow to the regional geology and ground-water hydrology, is considered to be pertinent to the hydrology of the basin at all seasons. Measurements of stream discharge and of the mineral constituents in selected water samples, however, provide only fleeting glimpses of the continually changing conditions in the basin. Important clues as to the basic hydrologic relationships may be derived by analysis of these reconnaissance data for the entire course of the stream in relationship to the continuing records from established gaging stations along the Colorado River and its tributaries.

Since 1946 four reconnaissance trips have been made by boat down the Utah portions of the main stems of the Green and Colorado Rivers for the purpose of measuring all tributary inflow and determining the discharge of the main stems at numerous sections not included in the gaging-station network. These reconnaissance trips were made by the Water Resources Division of the Geological Survey, under the direction of M. T. Wilson, district engineer in Salt Lake City. Three of the trips were made in September and October of 1946, 1947, and 1948, when the discharges of the main stems and tributaries were at or near the minimum for the year. One trip was made in June 1947, during the period of maximum discharge from melting snow.

These reconnaissance trips provided valuable data as to the tributary inflow and other hydrologic factors. In the 1948 reconnaissance the relation of stream flow to geology and ground-water hydrology received special attention. The data collected in that year also provided a better opportunity than had previous data to evaluate the effect of evapotranspiration losses and ground-water gains upon the inflow of the stream, for the following reasons: gaging stations recently established on the Green River near Jensen and near Ouray permitted analysis of the discharge at those points throughout the period of the reconnaissance; the discharge of the river in September 1948 was lower than at any time since 1940, and the gains and

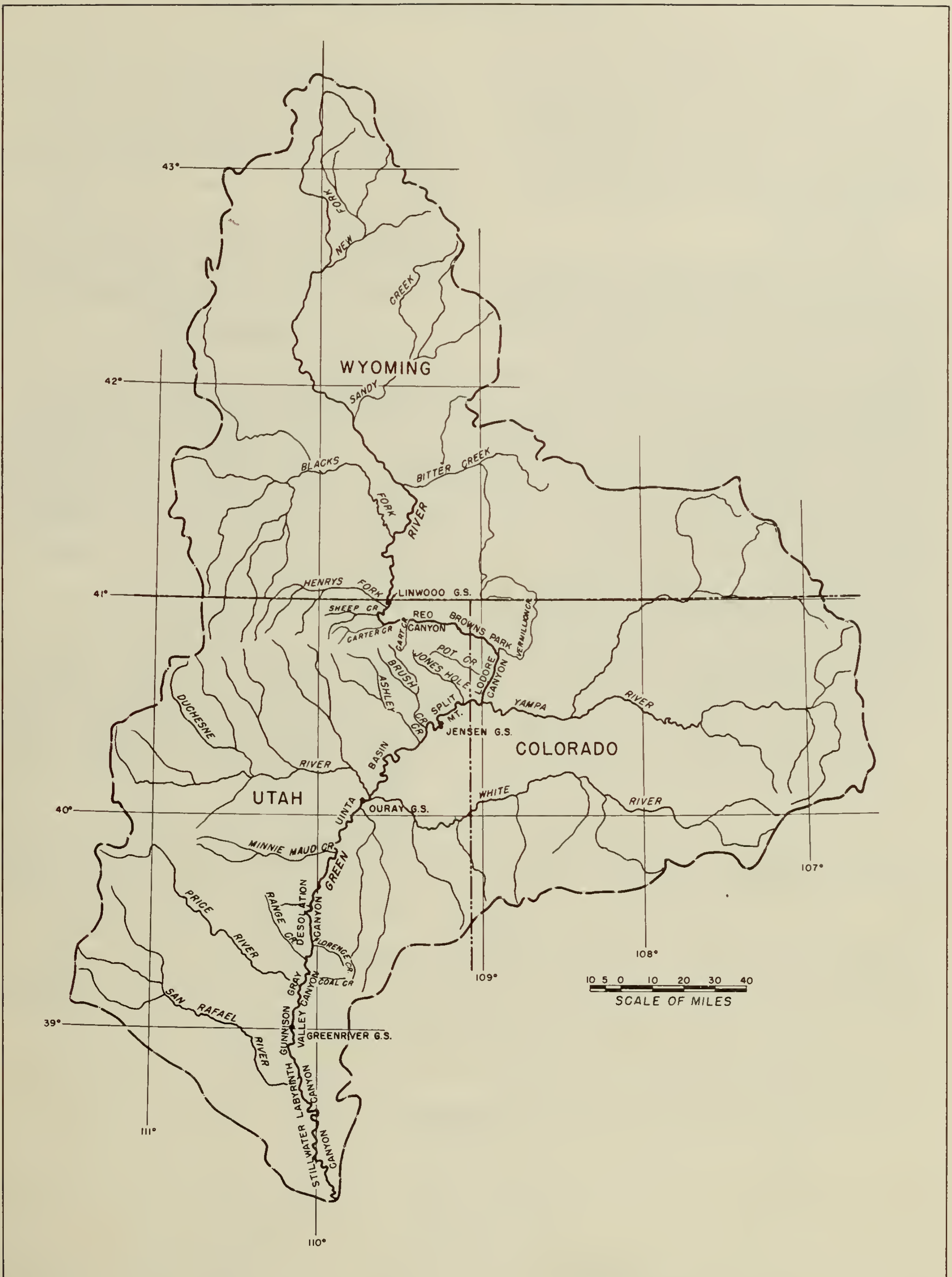

Figure 1.--Map of Green River basin.

losses by ground water were accordingly a larger proportion of the flow; and because of favorable meteorological conditions there was very little storm runoff during the 1948 reconnaissance, in contrast particularly to the condition during the 1946 trip, when storms created a flood wave with peak discharge more than double the minimum flow of the preceding week.

The 1948 reconnaissance of the Green River was made during the period September 14 to 29, and was followed October 1 to 7 by a reconnaissance of the Colorado River between Moab and Lees Ferry. The program for this reconnaissance included, as for previous trips, the measurement of the main-stem discharge at numerous sections and the determination of all tributary inflow. In addition, observations were made as to ground-water inflow, losses by evaporation and transpiration, and the geologic conditions that might be expected to affect the stream flow in the main stems. The reconnaissance party included the following personnel of the Geological Survey; the writer (Linwood to Lees Ferry), M. T. Wilson and Arthur Maxwell (Linwood to Jensen), Harold Chase (Linwood to Hite), Elmer Butler (Ouray to Green River), and Laphene Harris (Westwater to Lees Ferry). From Moab to Hite the party also included Neil Murdock, regional geologist, and Clyde Hardy, hydraulic engineer, of the Bureau of Reclamation, who investigated potential dam sites along the Colorado River in Cataract Canyon. W. R. Wayman, of the Utah Water and Power Board, accompanied the party from Hite to Lees Ferry for the purpose of studying the potential development of Glen Canyon.

Water samples collected during the reconnaissance were analyzed in the laboratory of the Geological Survey in Salt Lake City, under the direction of C. S. Howard. Field engineers of the Geological Survey--Leon Jensen at Vernal, Warren Dean at Greenriver, and Jack Fehrson at Hite--collected additional field data and records of considerable value during the period of the reconnaissance.

This report includes a description of the geology and ground-water hydrology of the Green River channel below the Wyoming State line, based on data obtained during the several reconnaissance trips and on other published and unpublished information.

Available maps

The base maps used in reconnaissance were the river-profile sheets published by the Geological Survey. Parts of the main stem of the Green River were surveyed as early as 1904, and other parts as recently as 1922. The two published series of profile sheets provide continuous coverage of the river channel and canyon walls to a height of 300 ft or more above the river bed, throughout the course of the river in Utah and Colorado. This coverage is at a scale of 2 in. to the mile, with a 5-ft contour interval on most sheets for the river surface and a 20-ft interval for the adjacent slopes.

Mileage along the center line of the river channel is indicated on each series of profile sheets, but commonly a different point of origin is used for each series. For clarity of presentation, mileages along the Green River have been computed as distances above its confluence with the Colorado. The following table shows the coverage of the two series of profile sheets with mileage as shown on the sheets as well as mileage computed from the mouth of the Green River.

Plans and profiles of Green River in Utah and Colorado

Reference[1]	No. of sheets	Year surveyed	Scale	Coverage (miles above confluence with Colorado River)[2]
A	9	1904-22	1:31,680	Greenriver, Utah - Wyoming State line 117.3 (0) 438.7 (321.4)
B	6	1914	1:31,680	Mouth of Green River - Greenriver, Utah 0 (0) 117.3 (117.3)

1 A, Plan and profile of Green River from Greenriver, Utah, to Green River, Wyo. 10 plan sheets and 6 profile sheets, U. S. Geol. Survey, 1924.

B, Plan and profile of Green River from mouth to Gunnison Butte, Utah: U. S. Geol. Survey Water-Supply Paper 396, p. 13-21, 1917.

2 Corresponding mileages printed on profile sheets are shown in parentheses.

Topographic maps, essential to an adequate analysis of the hydrology of the main stems and of the drainage basins of ungaged tributaries, were available for only a small portion of the route covered in the 1948 reconnaissance. About 150 miles of the course of the Green River is included on the following map, of which about 60 miles is covered by the excellent map of the Dinosaur National Monument.

Topographic maps covering channel of the Green River in Utah and Colorado

Quadrangle	Scale	Mileage above mouth
Marsh Peak	1:125,000	439 to 415
Dinosaur Monument	1: 62,500	264 to 303
Jensen	1:125,000	303 to 292
Vernal	1:125,000	292 to 234

Geologic maps cover a far greater proportion of the area traversed by the Green River than do topographic maps, but many of them are of reconnaissance type and are published at small scales. All published maps lack the topographic base which is highly desirable for interpreting physiographic forms on the basis of geologic structure and stratigraphy.

Geologic maps covering channel of the Green River in Utah and Colorado

Author	References	Scale	Mileage above mouth of river
A. R. Schultz	USGS Bull. 702	1:250,000	439 to 361
G. E. Unterman	Unpublished	1: 62,500	360 to 303
H. S. Gale	USGS Bull. 415	1:125,000	303 to 290
P. T. Walton	GSA Bull. 55	1:650,000	336 to 210
D. J. Fisher	USGS Bull. 852	1: 62,500	139 to 117
E. T. McKnight	USGS Bull. 908	1: 62,500	117 to 0 (area east of river)
A. A. Baker	USGS Bull. 951	1: 62,500	117 to 0 (area east of river)

GEOLOGY AND GROUND WATER HYDROLOGY

General statement

The Green River in its course from the Wyoming State line to its junction with the Colorado River crosses two major geologic structures--the Uinta Mountain uplift and the broad trough whose deepest part forms the Uinta Basin. The rocks cropping out along the river are all of sedimentary origin and range in age from pre-Cambrian to Recent. The maximum thickness of the strata represented along the river totals nearly 65,000 ft. The accompanying diagram (pl. 1) shows a panoramic geologic sketch of the right bank of the river, and stratigraphic columns based upon recorded measurements of strata that crop out in the vicinity of the river.

References for stratigraphic columns on plate 1 are:

1. Flaming Gorge.	Reeside, 1925 (fig. 7) and Schultz, 1920, p. 36.
2. Browns Park.	Bradley, 1936, pp. 182-185.
3. Island Park.	Reeside, 1925, pp. 42-43.
4. Dinosaur Quarry.	Unterman, G. E., and B. R., 1945. 10 pp.
5. Asphalt Ridge.	Walton, 1944, p. 92.
6. Ouray.	Walton, 1944, pp. 96-123.
7. Greenriver.	Fisher, 1936, pp. 8-21.
8. Jack Creek.	Baker, 1946, pp. 22-92.

The geologic formations of the region are listed in the following tabular summary.

Generalized stratigraphic columns for the Green and Colorado River canyons in Utah

	Uinta north slope[a]	Uinta Basin[b]	Green River Desert[c]	Glen Canyon[d]
TERTIARY (T)				
PLIOCENE	Browns Park formation, max 1,200 ft			
MIOCENE	Bishop conglomerate, max 500 ft			
OLIGOCENE		Duchesne River formation, max 1,500 ft		
EOCENE	Bridger formation, max 1,000 ft	Uinta formation, max 1,650 ft		
	Green River formation, max 1,500 ft	Green River formation, max 1,800-2,400 ft		
	Wasatch formation, 1,000-2,500 ft	Wasatch formation, max 780 ft	Wasatch formation, 250-4,000 ft	Wasatch formation

Generalized stratigraphic columns for the Green and Colorado River canyons in Utah--Continued

	Uinta north slope[a]	Uinta Basin[b]	Green River Desert[c]	Glen Canyon[d]
TERTIARY(T) Continued	Post-"Laramie" formation, 6,000-9,400 ft			
CRETACEOUS (K)	"Laramie" formation 1,500 ft			
	Lewis Shale 750 ft		Tuscher formation, 130-600 ft	Kaiparowits formation max 2,000 ft
	Mesaverde formation, 2,100-3,350 ft	Mesaverde group, max 3,100 ft	Mesaverde group 1,520-3,050 ft	
	Hilliard shale 3,800-4,800 ft	Mancos shale 800-6,200 ft	Mancos shale 1,400-4,120 ft	Wahweap sandstone, 1,200-1,300 ft Straight Cliff sandstone
	Frontier formation 125-500 ft			Tropic shale 600-1,400 ft
	Aspen shale 135-200 ft			
		Dakota formation max 330 ft	Dakota formation max 180 ft	Dakota sandstone max 200 ft
JURASSIC (J) SAN RAFAEL GROUP	Beckwith formation max 1,500 ft	Morrison formation 780-800 ft	Morrison formation 480-950 ft	Morrison formation, 525-1180 ft
			Summerville formation, 25-205 ft	Summerville formation, 40-500 ft
		Curtis formation 90-260 ft	Curtis formation max 235 ft	Curtis formation, max 175 ft
		Entrada sandstone, 130-160 ft	Entrada sandstone 230-460 ft	Entrada sandstone, 10-1,070 ft
	Twin Creek limestone 140-200 ft	Carmel formation 70-125 ft	Carmel formation max 230 ft	Carmel formation, max 560 ft
GLEN CANYON GROUP	Nugget sandstone 1,000 ft	Navajo sandstone 700-1,000 ft	Navajo sandstone max 550 ft Kayenta formation 150-320 ft	Navajo sandstone 400-1,350 ft Kayenta formation, max 320 ft.
			Wingate sandstone 210-370 ft	Wingate sandstone 300-430 ft
TRIASSIC (Ћ)	Ankareh shale 300 ft	Chinle formation 220-260 ft	Chinle formation max 740 ft	Chinle formation 200-980 ft
	Thaynes formation max 300 ft	Shinarump conglomerate, 50-60 ft	Shinarump conglomerate, max 135 ft	Shinarump conglomerate, max 250 ft
	Woodside shale 300-500 ft	Moenkopi formation, 800-1,075 ft	Moenkopi formation max 940 ft	Moenkopi formation, 250-685 ft

Generalized stratigraphic columns for the Green and Colorado River canyons in Utah--Continued

	Uinta north slope[a]	Uinta Basin[b]	Green River Desert[c]	Glen Canyon[d]
PERMIAN (P)	Park City formation 200-450 ft	Park City formation, 50-470 ft		Kaibab limestone max 600 ft
			Cutler formation max 1,850 ft	Cutler formation, 1,000-1,600 ft
			Rico formation max 585 ft	Rico formation 300-325 ft
CARBONIFEROUS (C) PENNSYLVANIAN	Weber quartzite 1,000-2,000 ft	Weber sandstone 800-1,450 ft	Hermosa limestone max 1,800 ft	Hermosa formation, 1,800-2,000 ft
	Older Pennsylvanian limestone, 1,000-2,100 ft	Morgan formation 1,400 ft	Paradox formation max 3,900 ft	
MISSISSIPPIAN	Mississippian limestone 1,000-2,500 ft	Madison limestone 600 ft		Redwall limestone
CAMBRIAN (€)	Undifferentiated 1,500 ft	Lodore formation 380-3,000 ft		
PRE-CAMBRIAN (p-€)	"Uinta" group 13,000 ft Red Creek quartzite	Uinta Mountain group 12,000 ft		

a Schultz, 1920, pp. 24, 36; b Unterman, G. E., and B. R., 1945, 10 pp.; Walton, 1944, pp. 91-130; c Fisher, 1936, 104 p.; Dane, 1935, 184 pp.; McKnight, 1940, 147 pp.; d Gregory, 1938, 123 pp.; Gregory and Moore, 1931, 161 pp.; Hunt, 1946, 51 pp.

The geologic and ground-water conditions encountered along the channel of the Green River are summarized in succeeding sections, for the physiographic subdivisions listed in the accompanying table.

Physiographic subdivisions of the Green River channel in Utah and Colorado

Name	Mileage above mouth	Altitude (feet)	Length (miles)	Average gradient (ft/mile)	Predominant rocks along channel
Wyoming State line	438.7	5,853			
Lucerne Valley			3.3	1.8	Cretaceous shale
	435.4	5,847			
Horseshoe and Kingfisher Canyons			10.5	2.3	Jurassic and Carboniferous sandstone and shale
	424.9	5,823			
Red Canyon			29.4	11.9	Pre-Cambrian quartzite
	395.5	5,473			
Browns Park			35.2	3.9	Tertiary sandstone
	360.3	5,335			
Lodore Canyon			16.7	15.8	Pre-Cambrian quartzite
	343.6	5,071			
Echo Park			3.5	4.6	Carboniferous sandstone
	340.1	5,055			
Whirlpool Canyon			8.6	11.4	Pre-Cambrian quartzite, Cambrian sandstone, Carboniferous limestone
	331.5	4,957			
Island Park			7.2	3.5	Jurassic and Triassic sandstone
	324.3	4,932			
Split Canyon			7.3	20.1	Carboniferous limestone and sandstone
	317.0	4,785			
Uinta Basin			129.8	1.5	Tertiary and Cretaceous shale and sandstone
	187.2	4,585			

Physiographic subdivisions of the Green River channel in Utah and Colorado--Continued

Name	Mileage above mouth	Altitude (feet)	Length (miles)	Average gradient (ft/mi)	Predominant rocks along channel
Desolation Canyon			31.2	6.5	Tertiary sandstone
	156.0	4,283			
Gray Canyon			26.5	7.1	Cretaceous sandstone
	129.4	4,095			
Gunnison Valley			34.5	3.3	Cretaceous and Jurassic
	94.9	3,982			
Labyrinth Canyon			59.9	1.0	Jurassic and Triassic sandstone and shale
	35.0	3,921			
Stillwater Canyon			35.0	1.3	Permian sandstone, Carboniferous limestone
Mouth of Green River	.0	3,877			

Lucerne Valley

For the reconnaissance in 1947 and 1948 the party put the boats into Green River near the head of Red Canyon, just below the mouth of Sheep Creek, which enters the river 426 miles above its mouth. No opportunity was afforded to inspect Lucerne Valley, Flaming Gorge, Horseshoe Canyon, or the upper part of Kingfisher Canyon, and the following remarks are therefore based largely upon the report of an earlier reconnaissance by Reeside (1925).

Stratigraphy and structure.-The rocks cropping out at the edge of the flood plain near the mouth of Henrys Fork are identified as the Hilliard shale of Upper Cretaceous age, equivalent to the upper part of the Mancos shale south of the Uintas. The effect of arching by the Uinta uplift is shown by the increasing inclination of beds southward from the Wyoming State line. At the mouth of Henrys Fork (mile 436 above the mouth of Green River) the dip is nearly vertical.

Flaming Gorge and Horseshoe and Kingfisher Canyons

From the lowlands through which it enters Utah from Wyoming, the Green River passes through Flaming Gorge, with walls as much as 1,200 ft high, and then follows a meandering course alternately through small open valleys and box canyons.

Stratigraphy and structure.-The several physiographic divisions through which the river flows are parts of a single geologic unit, which consists of a series of hard and soft beds with northeast strike and steep northwest dips, on the north flank of the Uinta arch. The Nugget sandstone of Jurassic age (equivalent to the Navajo sandstone) forms the crest of the north wall of Flaming Gorge and of Neilson's Flat, which separates Horseshoe and Kingfisher Canyons. Beneath this sandstone are the colorful beds of the Triassic Ankareh shale, Thaynes formation, and Woodside shale, which appear to be similar in lithology to the Chinle and underlying Moenkopi formations farther south. The soft shales of the upper part of the Park City formation of Permian and Pennsylvanian age are at river level under the rim of the Nugget sandstone, and both the river and Sheep Creek have wide valleys (Neilson's Flat) where they cross the outcrop of the Park City. Still farther southwest the resistant beds of the lower part of the Park City formation and the underlying Weber sandstone crop out, and in them the river has cut the meander-loop box canyon known as Horseshoe Canyon, and below Neilson's Flat another box canyon called Kingfisher Canyon. The Uinta fault forms the dividing line between Kingfisher Canyon, cut in steeply dipping Weber sandstone and Red Canyon.

Ground-water hydrology.--The channel between Flaming Gorge and the head of Red Canyon was not studied during the 1948 reconnaissance for evidence of ground-water inflow. Previous reconnaissance, however, had covered this channel and it is known that no large springs occur along its banks. The geologic formations cut by the river, except the Weber sandstone and the Nugget sandstone, yield practically no water where penetrated in other parts of the State. Only a very small quantity of water, if any, would be expected from the Weber sandstone, because its outcrop area is cut off within a short distance of the river by the Uinta fault, and the water in the Nugget sandstone would be limited to that which enters the rim north of Flaming Gorge and Neilson's Flat.

Red Canyon

Through Red Canyon the river follows a generally eastward course between canyon walls that are as much as 1,800 ft above the stream bed, vertical in places but more generally at moderate inclination. Steep talus slopes flank the bedrock walls in many places. Plant associations along the canyon walls are alpine, as conifers replace the sagebrush that is characteristic farther north.

Stratigraphy.--Red Canyon is cut entirely in the hard quartzitic sandstones and conglomerates of the pre-Cambrian Uinta Mountain group, and all tributaries entering Green River in this canyon (except Red Creek) drain outcrop areas of the same rocks. The quartzite (from which the canyon receives its name) is commonly in massive dark red beds, and has prominent joints.

Structure.--The entrance to Red Canyon is marked by the Uinta fault, which brings the

pre-Cambrian rocks into contact with the Weber sandstone. Throughout the canyon the quartzite dips 10° to 20° NW, forming part of the north flank of the broad Uinta anticline. The lower end of the canyon is marked by another fault which forms one side of the Uinta Mountain graben occupied in part by Browns Park (Bradley, 1936).

Ground-water hydrology.--The quartzite group of the Uinta Mountain is dense and well cemented and appears to be practically impermeable, so that ground water probably occurs only along the bedding and joint planes. Several of the tributaries entering Red Canyon from the south were contributing to the Green River water that originated in the high central part of the Uinta Range. No inflow was observed from any of the tributaries entering Red Canyon from the north. These tributaries have drainage basins at altitudes generally lower than those south of the river, and ground water moving down the dip of the bedding planes would move away from the Green River. Climatologic records show no storms in the area for a period of 18 days previous to the 1948 reconnaissance, and the tributary inflow observed in that period is concluded to be base flow, derived from ground water.

The Uinta fault might be expected to produce springs, derived from water that has moved down the dip of the quartzite beds. The spring that furnishes the water supply for the forest camp area known as Innes Gardens (mile 425) appears to originate in this manner. About 0.1 cfs was flowing into the camp on September 13, 1948, but it seeped entirely into the flood plain and none flowed directly into the river.

Small seeps were observed at the bases of the alluvial cones at the mouths of several tributaries, especially of Carter and Cart Creeks. These seeps rose only a few inches above the river surface, and it is likely that additional ground water moves directly into the river. The water is evidently derived from the porous gravels under the beds of the respective tributaries. Earlier in the summer the rate of seepage had been greater, and the water had eroded channels as much as 2 ft deep in the loose Recent deposits along the river bank. All these channels headed below the 1948 high-water line of the river. Part of the seepage may have been derived from bank storage along the river during the high-water stage, but the chief source was doubtless the tributary area.

Browns Park

From Red Canyon the Green River emerges into a comparatively low area, in which sandstone and terrace gravels form the banks of the stream, although rugged ranges are seen in the distance both north and south, bordering the area that is known as Browns Park. Here the river has a lesser gradient and slower current in a wide, shallow channel, bordered by a broad flood plain upon which is luxuriant vegetation. The bedrock floor on which the alluvial and lacustrine beds accumulated is irregular, and in several places, notably in Swallow Canyon, the river has cut its channel into the bedrock. On some maps the portion of Browns Park west of Swallow Canyon is titled "Little Browns Park."

Stratigraphy.--The sedimentary rocks cropping out in Browns Park are beds of the Tertiary Browns Park formation, which includes a basal conglomerate white sandstone indicative of arid climate during its deposition, and some tuffaceous beds. This formation is soft enough that the river has developed a wide flood plain across its outcrop. Terrace gravels cover many of the graded slopes in the lower part of the valley, as seen from the river channel. Quartzite of the Uinta Mountain group forms the main Uinta Range to the south, as well as Cold Spring Mountain north of Browns Park. It has been exposed also along the channel of the river in Swallow Canyon, and in smaller areas east of the mouth of Beaver Creek and north of Cottonwood Creek.

Structure.--The beds of the Browns Park formation where seen along the river dip gently northeastward. These beds are unconformable upon the quartzite, which dips 8° to 15° S. in Swallow Canyon and in the area farther east.

Ground-water hydrology.--The permeable terrace gravels and coarse beds of the Browns Park formation act as a sponge to absorb water from melting snow or heavy precipitation in Browns Park, as well as much of the tributary inflow. This ground water evidently moves down the dip of the permeable beds and reappears at lower elevations, particularly along the edge of the flood plain of the river. As a result, cottonwoods and other phreatophytes (plants dependent upon ground water) commonly line the outer edges of the flood plain. Because of the general eastward dip of the gravels, flood-plain areas west of the meandering river bear salt grass and alkali patches, indicating a high water table during at least parts of the year. Over extensive areas of the flood plain the water table is practically at the surface even in late September, and gives rise to tule and cattail swamps and some stagnant ponds.

Although several of the tributaries entering Browns Park have large drainage basins and head at high elevations on the plateaus to the north and south, practically no surface flow reached the river in September 1948, probably because of high evapotranspiration draft near the mouth of each tributary. No springs or seeps were seen along the banks of the river throughout Browns Park. In one area artificial high-water channels divert water from the river onto the flood plain. Originally this diversion, together with drainage channels back to the river, was for irrigation of wild hay and pasture. The cutting of hay for livestock feeding during winter months has been discontinued and drainage channels have not been maintained. This condition has increased the area of swamp and stagnant ponds.

Lodore Canyon

At the southeast end of Browns Park the Green River passes through the spectacular Gate of Lodore and enters Lodore Canyon. The river pursues an exceptionally straight course through this canyon, which is about 17 miles long, and has a steeper gradient than in Red Canyon. The canyon walls are about 2,200 ft high at the Gate of Lodore.

and reach a maximum height of about 2,900 ft near Rippling Brook.

Stratigraphy.--At its north end Lodore Canyon is cut entirely into the quartzites of the Uinta Mountain group. These beds crop out in the bottom of the canyon as far south as Alcove Brook (mile 344 above the mouth) but the sandstones and shales of the Lodore formation of Upper Cambrian age appear at the top of the canyon walls near Pot Creek (mile 351). The massive Madison limestone (Carboniferous) forms Limestone Ridge east of the canyon at Triplet Falls (mile 350) and becomes progressively lower to the south, cropping out at river level in the southern part of Lodore Canyon, where the overlying Morgan formation and Weber sandstone forms the walls.

Structure.--The quartzite of the Uinta Mountain group and the overlying Paleozoic rocks have a general southward dip throughout Lodore Canyon. In detail there are several broad folds which have been cut by the river, so that in places the beds are horizontal and in others they dip as much as 25°. Lodore Canyon ends at the Mitten fault (mile 344), which is prominent along the right (west) bank but appears to die out in the river channel to the east.

Ground-water hydrology.--The quartzite of the Uinta Mountain group carries some water, as shown by a few springs along the walls of the northern part of the canyon. One of these at the Wade and Curtis lower cabin (mile 358) appears at the base of a quartzite bed about 300 ft above the channel, and others are indicated by small groups of phreatophytes along the canyon walls. phreatophytes near the heads of the alluvial cones of minor tributaries indicate that those tributaries carry some ground water into Lodore Canyon.

The formations of Carboniferous age--the Madison limestone, Morgan formation, and Weber sandstone--are relatively productive aquifers, in which water moves generally southward down the dip of the beds and appears in springs in numerous tributaries, as shown on the topographic map of the Dinosaur National Monument. Except for a small seep at the lower end of the canyon, near the Mitten fault, no springs were observed along the outcrops of the permeable Madison limestone in the floor of Lodore Canyon. This is attributed to the fact that the same beds are cut farther north by the canyon, which leaves a very small recharge area.

The Madison limestone crops out at river level in the lower mile of Lodore Canyon, and the beds have a southward dip of 15°. The bedrock of the south wall of the canyon (left bank) is separated from the channel by talus slopes. The river bed here is about 5,075 ft above sea level. The river may lose water by seepage into this limestone, provided there are outcrops, faults, or other permeable zones farther south, where the water may be discharged at lower altitude. Stream-flow measurements indicated no large losses in this section during the reconnaissance of September 1948. During high stages, however, there are significant unexplained losses from the Green River between Linwood and Jensen. Our present knowledge of the geology and hydrology of the Madison limestone is inadequate to be a basis for judging how much, if any, of these river losses are due to seepage into the limestone here in Lodore Canyon, or in Whirlpool Canyon (p. 11).

The proposed Echo Park dam will impound water to depths as great as 500 ft upon the outcrops of Madison limestone in Lodore Canyon. It is not known whether this increased head may cause significant increases of seepage into the limestone, and therefore significant losses from the reservoir.

None of the tributaries in Lodore Canyon carried any surface water into the Green River at the time of the 1948 reconnaissance. Several of these are spring-fed, and are shown on the topographic map as perennial to the south. The lack of flow at this season may signify a marked fluctuation in discharge of the springs, or it may indicate that all the water from these springs moves to the river through the porous alluvium of the tributary channels.

Echo Park

On leaving Lodore Canyon, the Green River makes a sharp U-bend around Steamboat Rock, a long, narrow ridge 1,000 ft high, with a vertical wall on the east side and almost as steep a slope on the west. The Yampa River flows into the Green River east of Steamboat Rock. Elsewhere the outer wall of the U-bend is formed by cliffs nearly as steep as Steamboat Rock, but the floor of the canyon is wide enough to permit a small agricultural development near the mouth of Pool Creek, which enters Green River from the south.

Stratigraphy and structure.--At the upper end of Echo Park the varicolored limestone and shale beds of the Morgan formation are in fault contact with the older Madison limestone, and have been dragged along the Mitten fault until the beds approach verticality. Farther south, with gentle dips northward, the Weber sandstone overlies the Morgan. Steamboat Rock is formed almost entirely by the Weber, but has a thin cap of the Park City formation. Turning northward, the river again crosses the Mitten fault, which thus forms both ends of Echo Park. At this lower crossing there is a marked drag to the beds on both sides of the fault. The throw of the fault is much greater than farther east, and the Morgan formation is brought down into contact with the quartzite beds of the Uinta Mountain group.

Ground-water hydrology.--The alluvium that forms the valley floor in Echo Park is permeable sand and gravel. During periods of low flow some of the discharge of the Yampa and any discharge from Pool Creek probably occur by subsurface flow in the alluvium, so that the observed surface inflow may not represent the entire contribution to Green River in Echo Park. The Weber sandstone, which forms the walls of most of Echo Park, is one of the few permeable rocks cut by the Green River in Utah. Cottonwood trees growing on the lower west slope of Steamboat Rock probably depend on water moving in this sandstone from the Green River channel east of the Rock. This channel drops 15 ft in its course around Steamboat Rock.

A spring along the Mitten fault at the lower end of Echo Park discharges more than 1 cfs. The temperature of the water (62 F) indicates that the source is not deep, and probably the principal source is the Green River where it crosses the fault at the mouth of Lodore Canyon, three-quarters of a mile to the east and 15 ft higher in elevation.

Whirlpool Canyon

From Echo Park the river enters Whirlpool Canyon, which is exceedingly narrow at its upper end, at the site of the proposed Echo Park dam. Farther west the floor of the canyon is wider, but beginning some distance above the channel its sides are composed of nearly vertical cliffs. The canyon wall south of the river is especially steep, and rises to elevations more than 7,500 ft above sea level and 2,500 ft above the river. The north wall rises more gently to a crest more than 7,800 ft above sea level.

Stratigraphy.--The pre-Cambrian quartzite crops out at river level in the upper 1.7 miles of Whirlpool Canyon, and the Paleozoic section up to the Morgan formation is exposed in the canyon walls. To the west the micaceous shales and thin-bedded sandstones of the Lodore formation form the canyon floor for a distance of 3 miles, to a point three-quarters of a mile downstream from the mouth of Jones Hole Creek. The canyon floor is fairly wide in this reach, but the hard limestones of the Madison and Morgan formations form cliffs on both sides. Farther west the Madison limestone crops out at river level for a distance of 2½ miles, and the Morgan formation is exposed at river level in the lower half mile of Whirlpool Canyon.

Structure.--In the upper part of Whirlpool Canyon the entire sedimentary series has a gentle southward dip, ordinarily between 5° and 10°. Southwestward from the mouth of Sage Creek the river parallels the trace of the Island Park fault, and eventually crosses it at the lower end of Whirlpool Canyon, just east of the mouth of Red Wash. The upthrown side of this fault is to the southeast, and steeply inclined beds of the Weber sandstone and Morgan formation, dragged along the fault, are seen at the mouth of Whirlpool Canyon and in the canyon of Sage Creek a short distance above its mouth.

Ground-water hydrology.--All springs observed in Whirlpool Canyon are on the north side of the channel, indicating that ground water moving southward down the dip of the strata is intercepted in the deep canyon of the river. Springs occur in the pre-Cambrian rocks near Wild Canyon, and there are numerous springs near the base of the Lodore formation and some at higher levels within that formation. By far the most important aquifers along this reach of the river, however, are the limestones of the Madison and Morgan formations, of Carboniferous age. Jones Hole Creek, the largest tributary to the Green River in Whirlpool Canyon, derives most of its flow from a group of springs about 4 miles upstream from the mouth, at an elevation about 5,600 ft above sea level. G. E. Unterman (oral communication), who has mapped the geology of the Dinosaur Monument area, states that the springs rise from the lower part of the Morgan formation. Measurements in the reconnaissance of 1946 to 1948 indicate that these springs contribute to the Green River a fairly constant flow of 30 to 35 cfs, and springs around the base of the creek's alluvial fan yield an additional second-foot of water. In several places in Whirlpool Canyon west of Sage Creek the river channel is bordered by abutting and in places overhanging walls of cavernous limestone of the Madison and Morgan formations. Search along the north bank did not reveal any spring inflow at the time of the 1948 reconnaissance, but in some places the deepest part of the channel lay against the wall and appreciable inflow may have been occurring. There is also the possibility of losses from the river in the lower part of Whirlpool Canyon, where the channel lies against limestone cliffs on the left (south) bank, and where seepage from the river may be moving southward down the dip of the formation.

The upper part of Whirlpool Canyon--east of Jones Hole Creek--cuts entirely through the limestone of the Morgan and Madison formations, and thus might be expected to intercept any ground water moving from the north in these formations. Appreciable contributions to the river may be made by subsurface flow through the talus slopes that lie north of the channel, and thence direct to the alluvium of the channel. Stream measurements indicate that there was inflow to the Green River between the mouth of the Yampa and Jensen in excess of the surface inflow of tributaries. The places where this unseen inflow is most likely to occur are the zones in Whirlpool Canyon and Split Mountain Canyon where the Madison and Morgan formations crop out at or above river level.

Island Park area

The Island Park area is along the river between Whirlpool and Split Mountain Canyons. The area includes three subareas of rather broad flood plains, locally named Island Park, Rainbow Park, and Little Park, separated by low ridges. The river channel is broad, shallow, and meandering, and contains several large islands covered with willows and cottonwoods.

Stratigraphy.--The Navajo sandstone of Jurassic (?) age lies at the entrance to the Island Park area and appears to underlie most of the floor of the northernmost (Island) park; it is covered extensively by terrace gravels. Younger Jurassic formations are seen on the ridge that separates Island Park from Rainbow Park. The Morrison formation of Upper Jurassic age forms the summit of this ridge and crops out near river level in the lower part of the area.

Structure.--The rocks of the Island Park area form a syncline whose axis plunges to the east. According to Unterman (oral communication), the Mancos shale is at the surface in the trough of this syncline, but its outcrops are not seen from the river. The Island Park area is bordered on the east by the Island Park fault, which has truncated the syncline and brought the Weber sandstone

into contact with the formations of Mesozoic age that are exposed in the area. At the lower end of the Island Park area the river recrosses this fault and enters Split Mountain Canyon.

Ground-water hydrology.--Island Park, like Browns Park, appears to contribute nothing to the late summer flow of Green River. Neither tributary inflow, springs, nor evidence of subsurface inflow was observed throughout this reach of the stream. On the other hand, there are extensive areas of phreatophyte growth, and undoubtedly there is some depletion of the river during the summer as a result.

Split Mountain Canyon

Both the entrance and exit to Split Mountain Canyon are spectacular because of the highly inclined strata of sandstone. The canyon is more than 2,800 ft deep, its walls rising to the summits of Split Mountain and the Yampa Plateau more than 7,600 ft above sea level. The average gradient through the canyon is 20 ft per mile, which is steeper than that of any other canyon along the Green or Colorado Rivers in Utah.

Stratigraphy and structure.--The rocks of Split Mountain Canyon form a sharp anticline with an east-west axis. The river crosses the north flank of this anticline at right angles to the strike and then turns and follows the axis of the fold for nearly 5 miles before turning southward across the south flank. The Weber sandstone is the youngest formation exposed. It crops out on the flanks of the anticline at both ends of the canyon, and at the top of the canyon walls on Split Mountain and the Yampa Plateau. The Morgan formation appears at river level for more than a mile near the upstream end of the canyon, and also along the lower part of the canyon. The Madison limestone is exposed along the axis of the anticline for a distance of about 3 miles, and the river has cut about 400 ft into the formation in the center of its outcrop area. Unterman's study of the regional geology has shown that this outcrop occurs at a minor flexure on the general anticlinal structure, which is in alinement with the east-trending Yampa fault farther east. That fault, with downthrown side to the north, dies out in the headwaters of Moonshine Draw, which enters Green River near the east end of Split Mountain Canyon.

Ground-water hydrology.--Warm springs flow into the river from both sides of the channel at a point about 2 miles above the lower end of the canyon (mile 319.4 above the mouth of Green River). These springs rise from cavernous beds near the top of the Madison limestone, or possibly at the base of the Morgan formation. From several springs above river level the estimated discharge was 6 cfs on September 18, 1948. Although some of these openings are above the high-water level of the river, most of the flow in September 1948 was coming to the surface only 1 or 2 ft above river level. Movement of spring water into the main channel below the level of the river surface was observed in shallows along the river's edge. It is certain, therefore, that there is additional spring discharge directly into the river, and this flow appears to equal or exceed that observed above the river. The spring openings are approximately 4,820 ft above sea level.

The temperature of the water from the several spring openings is 86 F, indicating that the water rises from considerable depth. As shown in the tables of chemical analyses, the water from these springs is more highly mineralized than that of Jones Hole Creek, which likewise comes largely from springs near the base of the Morgan formation.

Probable source of warm springs.--The limestones from which the warm springs issue are buried under at least 6,000 ft of younger sedimentary rocks in the Island Park syncline north of Split Mountain. As shown by Forrester (1939), however, these limestones (the Madison limestone and the "intercalated series") appear at the surface again along the south flank of the main Uinta Range, in the headwaters of Pot Creek about 15 miles north of Split Mountain Canyon. Detailed maps are not available for this area, but it is believed that the altitude of the outcrop area along Pot Creek generally exceeds 8,000 ft.

The warm springs are considered to be artesian springs, dependent on this high outcrop area for recharge. The water as it moves southward must go down to considerable depth under the younger sedimentary rocks in the Island Park syncline, and the temperature is increased appreciably. As the water moves under artesian pressure up the north flank of the Split Mountain anticline, there is some loss of heat to the limestone, and the temperature at the spring openings is only moderately higher than the average annual temperature of the region.

Uinta Basin

Leaving Split Mountain Canyon, the river cuts across the upturned edges of strata along the flanks of Split Mountain, and within a mile begins a meandering course across extensive lowlands composing the Uinta Basin. Gently dipping sediments are the rule, the resistant beds forming low ridges or terraces and the softer rocks being poorly exposed on the valley bottoms and slopes. Sagebrush associations are characteristic except where ground water is close to the surface. Small irrigated areas are seen along the main stem and larger tributaries.

Other geographic terms have been applied to portions of this reach of the river: Ashley Valley, in which the town of Vernal is situated, has been extended by some to include the portion of Green River between Split Mountain Canyon and the Asphalt Ridge (mile 293 from the mouth). Powell in 1873 applied the name "Wonsits Valley" to the area between Split Mountain Canyon and the mouth of the Duchesne River; Reeside (1925, p. 44), used the same name for the area above Willow Creek, and called the area between that creek and Minnie Maud Creek "Upper Desolation Canyon." In this report the form "Uinta Basin" is applied to the area along the river between Split Mountain Canyon and Jack Creek (24 miles below Minnie Maud Creek) because of the hydrologic characteristics of the stream throughout this reach. The river has a low gradient which decreases progressively from about 3 ft per mile near Brush Creek to 1 ft

per mile above Jack Creek, and the channel has very broad meanders. Above Jack Creek as far as Willow Creek the river is in a valley that is sharply confined by steep slopes and cliffs, but the channel is still bordered by sizable though discontinuous flood plains. Rapids are encountered at Jack Creek at medium stage; below that creek, in what is here designated Desolation Canyon, the average gradient is $6\frac{1}{2}$ ft per mile and the course of the river is fairly straight.

Stratigraphy.--South of the Weber sandstone in Split Mountain Canyon the exposed strata include a succession of Permian, Triassic, and Jurassic rocks, dipping southward. The river enters the outcrop area of the Mancos shale within a mile of Split Mountain Canyon, and its channel is cut in this formation for 24 miles, as far south as the Asphalt Ridge (mile 293 from the mouth). At Asphalt Ridge the river crosses the outcrop of the Mesaverde group of Upper Cretaceous age, and is in Tertiary beds throughout the rest of its course in the Uinta Basin. The Wasatch and Green River formations of Eocene age, which overlie the Mesaverde, are shown by Walton (1944), to crop out along the river in the mile southwest of Asphalt Ridge, but exposures could not be seen from the river. The youngest of the Tertiary sedimentary units, mapped by Walton as the Duchesne River formation of Oligocene age, comprises the fluviatile sandstone seen along the river for the next 37 miles. Farther downstream the river cuts through progressively older Tertiary sedimentary rocks for the remainder of its course in the Uinta Basin.

Structure.--South of Split Mountain the river crosses a plunging syncline which lies between the Split Mountain anticline and the Blue Mountain anticline farther south. The river passes across the nose of the Blue Mountain anticline at Jensen but does not expose the base of the Mancos shale.

The Uinta Basin, a geographic term universally accepted by local residents, is also properly named as to geologic structure. It is a broad structural basin whose axis crosses the river approximately at the Horseshoe Bend (mile 278 above the mouth). At Horseshoe Bend the strata are approximately horizontal, but to the north and south the sedimentary rocks dip gently toward the axis. The syncline is asymmetrical and the strata on the north flank, toward the Uinta Range, are inclined somewhat more steeply than those on the south flank. In the southern part of the basin, south of the mouth of Willow Creek, the strata dip 1° to 5° N.

Ground-water hydrology.--Because of its size and geologic structure, the Uinta Basin might be expected to be a major contributor of ground water to the Green River. Water from the Uinta Range enters the coarse detritus that has accumulated along its south flank--the Recent alluvium, Pleistocene outwash, Bishop conglomerate, and Duchesne River formation--and then moves southward in the greatly inclined strata toward the axis of the syncline. South of the basin, water originating on the high Tavaputs Plateau (reaching elevations more than 9,000 ft above sea level) moves northward down the dip of the Tertiary sandstones toward the axis of the basin.

The river in traversing the basin has developed a meandering channel and a flood plain that is generally more than half a mile wide and in places more than 2 miles wide. The flood plain supports a heavy phreatophyte growth. The sediments with which the hydrologist is primarily concerned--the bed of the present channel, the alluvium of the flood plain, the higher river terraces, and the Duchesne River and Uinta formations which crop out in the axis of the basin--are all of fluviatile origin, are poorly sorted, and probably have a wide range in permeability. In the axial part of the basin these sediments are saturated to within a few feet below the level of the flood plain. Ground water originating within the Uinta Basin probably supports most of the vegetation along the Green River flood plain in and near the axis of the basin. Any contributions of ground water to the river occur by seepage to the channel of the river. No springs or seeps have been seen along the channel above river level during the boat reconnaissance.

Determination of the quantity of ground water contributed to the Green River within the Uinta Basin cannot be made by reconnaissance but would require a detailed ground-water study to determine the position of the water table, direction of ground-water movement, hydraulic gradients, and permeability of the water-bearing sediments. In a succeeding section of this report the ground-water contribution to the Green River is estimated indirectly by (1) measuring the gain in flow of the river within the Uinta Basin, and subtracting therefrom the observed inflow of tributaries; (2) computing the area of phreatophyte vegetation and estimating the evapotranspiration draft; and (3) determining the residual gain which is attributed to ground-water inflow.

Desolation Canyon

The slopes on both sides of the river, which becomes progressively higher and steeper below Willow Creek, assume the aspect of true canyon walls near the head of Desolation Canyon, which is taken to be at the mouth of Jack Creek. At low stages of the river riffles are encountered as far upstream as Tabyago Creek (5 miles below Minnie Maud Creek), but there is no increase in gradient until Jack Creek is reached, where the first rapids are encountered. The walls of Desolation Canyon are of the set-back pattern characteristic of alternating hard and soft horizontal strata, where the resistant layers form ledges and cliffs and the soft beds produce slopes.

Stratigraphy.--The river in its southward course through Desolation Canyon continues to cut into progressively lower beds of Tertiary rocks, as it has in the southern part of the Uinta Basin. The regional geology here has not been studied in detail, and the boundaries of lithologic units along the river are not well defined. As pointed out by Reeside (1925, p. 46) in his reconnaissance, gray to yellow shales with beds of oil shale, characteristic of the Green River formation, appear along the sides of the canyon for about 12 miles above the mouth of Minnie Maud Creek, and are present in the upper parts of the canyon slopes at Jack Creek. Massive brown sandstone under-

lies these shales and may be part of the Green River or of the underlying Wasatch formation, though it is typical of neither. Dark-red sandstones near river level at Jack Creek are more characteristic of the Wasatch formation, and the river channel is evidently in this formation throughout Desolation Canyon.

Structure.--Throughout Desolation Canyon the strata have a gentle northeast dip ranging from 1° to 2°.

Ground-water hydrology.--In Desolation Canyon, as in the southern part of the Uinta Basin, the fact of northward movement of ground water in the Tertiary sandstone beds is established by the presence of seeps along the north-facing cliffs wherever the course of the river is easterly or westerly. Many of these seeps are some distance above river level and yield only enough water in the autumn of the year to moisten the surface and deposit white salts. However, some springs contribute small amounts of water to the river. The largest springs observed are along the cliff half a mile south of the mouth of Three Canyon Creek; they were discharging about 1 cfs when visited in 1948. The Camel Rock Spring 3 miles farther south appear at the base of a bed of massive brown sandstone overlying red shale, and discharged about 0.5 cfs at that time.

Ground water also contributes to the river at the bases of the alluvial fans of several tributaries, most of which had no surface flow at the time of the reconnaissance. The visible flow was from small seeps only slightly above the river level; there may have been additional subsurface flow direct to the river.

Gray Canyon

At the head of Gray Canyon the river leaves the escarpment called the Roan Cliffs, which is formed of the reddish rocks that make up the high walls of the lower part of Desolation Canyon. On emerging from that canyon the river passes through open country between low bluffs for a short distance, and then cuts into gray rocks, from which the canyon receives its name.

Stratigraphy and structure.--The strata at river level in Gray Canyon are the beds of the coal-bearing Mesaverde group of Cretaceous age. In the upper part of the canyon, above Rattlesnake Creek, these beds are dominantly sandstone of the Price River formation, and thin coal seams are seen in the canyon walls near Coal Creek. Shale of the underlying Blackhawk formation (also of the Mesaverde group) crops out at river level at Rattlesnake Creek and forms the lower 200 ft of the canyon walls at the mouth of Price River. The beds exposed in Gray Canyon dip gently north and northeast.

Ground-water hydrology.--As in Desolation Canyon, there are several springs and seeps in the north-facing walls of Gray Canyon within a few feet above river level. Seeps are especially numerous along both sides of the canyon between Coal Creek and Rattlesnake Creek. These seeps arise from the sandstone beds near the base of the Price River formation, just above the shale beds of the Blackhawk formation.

Gunnison Valley

The end of Gray Canyon is marked by Swasey rapids, and the river then traverses a region of soft rock weathered into low, rounded hills. This belt of soft rock was selected as the route for U. S. Highway 50 and for the Denver and Rio Grande Western Railroad. The town of Greenriver, Utah, is located at the point where these transcontinental routes cross the river.

Stratigraphy and structure.--As was the case at Jensen, Utah, the transcontinental highway crosses the river where it has cut a broad valley in the Mancos shale, of Cretaceous age. The top of this shale forms the river bed at the mouth of Gray Canyon, and its base is not far below the surface in the town of Greenriver. South of the town the Morrison formation, also predominantly shale, appears at the surface. Near the "Crystal Geyser" the underlying beds of the San Rafael group crop out in a small area, but south of the geyser the Mancos shale is at the surface again, and the course of the river continues across the outcrop of the shales of this formation and of the underlying Morrison and Curtis formations as far as Dry Lake Wash (mile 99.5). Beds of the Entrada sandstone form the banks of the river between that wash and the mouth of the San Rafael River, which marks the head of Labyrinth Canyon. The formations throughout Gunnison Valley have a gentle north to northwest dip. Three or more faults with general northwest trend cross the river south of the town of Greenriver.

Ground-water hydrology.--Small springs and seeps rise along the west bank of the channel just above river level, in the vicinity of the town of Greenriver and farther north. Some of these seeps were observed to be just below irrigated fields, and practically all are considered to be return flow of water diverted from the river near the mouth of Gray Canyon and used for irrigation.

The Crystal Geyser on the left bank of the river is the Glen Ruby well drilled for oil in 1936, and is 2,627 ft deep. In periods of quiescence the water is less than 20 ft below the surface, surges somewhat, and yields a gas that is presumed to be carbon dioxide. About once an hour the water is forced from the well to a maximum height estimated to be about 100 ft, continues to flow out with diminishing velocity for 2 to 5 min and then subsides again. The discharge of the well is estimated to be equivalent to a continuous flow of about 0.5 cfs, and the temperature of the water is 61 F. Calcium carbonate is being deposited by the geyser water. Mound-shaped deposits of aragonite about 200 ft southwest of the well, and similar deposits on an island in the channel and along the west bank of the river, indicate that springs have discharged in this area, along the Little Grand fault, for a long time. The well evidently constitutes an outlet for the ground water, localizing the spring discharge at the present time.

Labyrinth Canyon

At the mouth of the San Rafael River the Green River enters Labyrinth Canyon, which has precipitous walls formed of sandstone. The canyon has a meandering course best exemplified at Bowknot Bend, where the river follows a course more than 10 miles long to reach a point only a mile from the starting point. Near its upper end the canyon is narrow and has rather low vertical walls, but in its lower part it is nearly a mile wide and more than 1,000 ft deep. The surrounding country has a maximum elevation of about 7,000 ft and is semiarid. The streams draining this country are intermittent and discharge into the Green River only during storms or the melting of accumulated snow. Many of the smaller streams enter Labyrinth Canyon by way of hanging valleys.

Stratigraphy and structure.--Formations of the San Rafael group crop out at the mouth of the San Rafael River and are the youngest formations exposed in Labyrinth Canyon. In the upper part of that canyon the channel is cut into the Carmel formation and the upper part of the canyon walls is composed of the Entrada sandstone of the San Rafael group. To the south the channel is cut into progressively older formations and continues between vertical walls of the Glen Canyon group as far south as Bowknot Bend (mile 68). In the lower 33 miles of Labyrinth Canyon the soft shales of the Chinle and Moenkopi formations crop out at river level, and the floor of the canyon is wide but bordered by steep, high walls of the overlying Glen Canyon group, comprising the Wingate sandstone, Kayenta formation, and Navajo sandstone. Throughout most of Labyrinth Canyon the strata dip gently northwest. An exception occurs near the Bowknot Bend, where the river crosses the nose of the Cane Creek anticline and the strata dip west and southwest.

Ground-water hydrology.--Labyrinth Canyon was not included in the 1948 reconnaissance, but no springs along the river channel were reported during earlier trips. Baker (1946, pp. 1, 14), and McKnight (1940, pp. 15, 16), describe the springs in the areas drained by the small tributaries to Labyrinth Canyon, and Baker gives a tabulation of the springs west of Labyrinth Canyon. Throughout the region the upper part of the Kayenta formation gives rise to numerous springs and seeps, evidently derived from the overlying Navajo sandstone. These springs commonly yield water of excellent quality, as do the small springs rising from the Navajo and Entrada sandstones. The Carmel and Moenkopi formations also produce several springs, some of which may discharge as much as 5 to 10 gpm, but many of these yield water of poor quality. A very few springs rise from the Shinarump conglomerate and the Morrison formation. The water discharged from springs ordinarily evaporates or seeps into the ground within a few feet of the spring openings, but perennial flow may be maintained in some tributaries for as much as 2 or 3 miles.

Stillwater Canyon

The high vertical walls which are within a mile of the channel at the mouth of Labyrinth Canyon trend away from the river to form the east-west escarpment known as the Orange Cliffs. At the head of Stillwater Canyon the river cuts into a resistant sandstone which forms the only riffle between the San Rafael River and the mouth of the Green River. The walls of the canyon here are low and rise gradually southward, attaining a height of about 1,200 ft at the lower end of the canyon.

Stratigraphy and structure.--In its course through Stillwater Canyon the river channel cuts progressively older Paleozoic formations. The Cutler formation of Permian age with its ledger-forming member (the White Rim sandstone) and underlying siltstone member (the Organ Rock tongue), underlies the channel and forms the walls of the upper 18 miles of the canyon. Downstream, the Rico formation, also of Permian age, crops out at river level to within 9 miles of the confluence with the Colorado. The Hermosa formation of Pennsylvanian age, consisting of massive gray cherty limestone and sandstone beds, appears in the lower 9 miles of Stillwater Canyon, and the walls are formed by the overlying Rico and Cutler formations. The strata of Stillwater Canyon have a gentle northwest dip.

Ground-water hydrology.--Only the lower end of Stillwater Canyon was seen during the 1948 reconnaissance. In the rest of the canyon the strata are similar to those exposed in Labyrinth Canyon farther upstream and in Loop Canyon on the Colorado River.

Recommended regional studies

The following hydrologic studies of the Green River in Utah and Colorado are recommended as highly desirable before development projects are undertaken in the areas to which they pertain.

1. Browns Park.--This area appears to be one of the best in the upper basin for developing the techniques required for the "inflow-outflow" method of measuring stream depletions, and for making quantitative determinations of losses by evapotranspiration and gains by ground-water inflow. The Green River and Vermilion Creek enter Browns Park via canyons where the inflow can be determined with reasonable accuracy, and the total outflow can be determined near the Gate of Lodore. Complete hydrologic mapping of Browns Park will probably yield definitive information on all hydrologic factors, which may prove useful in analyzing other areas where the individual factors cannot be segregated.

The investigation should include topographic maps at a scale of 1:24,000 for tributary drainage basins (excluding the Green River and Vermilion Creek); geologic maps, especially of Tertiary and Quaternary deposits in Browns Park, and extending to surrounding mountain passes; a network of precipitation stations sufficient to determine areal distribution; stream-gaging stations on Green River at entrance and exit to Browns Park, and on tributaries at the edges of Tertiary sedimentary rocks; maps showing areas covered by various species of phreatophytes; ground-water study of the flood plain, including a network of boreholes sufficient to permit preparing water-table maps and profiles and to show the water-bearing character of the alluvium; recording gages on selected wells on the flood plain and terraces, and on ponds on the flood plain; a Weather Bureau evaporation station,

including a class A land pan for collecting temperature, anemometer, and humidity records. The results of such a study would be of special value to the Upper Basin Compact Commission and to the States of Colorado and Utah.

2. Hydrology of the Paleozoic rocks in Echo Park reservoir site.--The problem of losses to be expected by leakage from the proposed Echo Park reservoir can be answered only by detailed study of the geology and hydrology of the area south of Lodore Canyon of the Green River and Bear Canyon of the Yampa River.

The investigation should include topographic mapping, at a scale of 1:62,500, of the area between the Dinosaur National Monument and the Uinta Basin and, at a larger scale, of potential reservoir areas; detailed mapping of the stratigraphy and structure in the area between the Yampa River and the Uinta Basin, and also along the Mitten fault, with emphasis on ground-water conditions, including springs and their sources, and piezometric surface as indicated by wells; determination of the source of the shallow water that supports the extensive phreatophyte growth in the Uinta Basin, south of the Echo Park area. These studies would be of especial value to the Federal Government and to the upper basin States in their planning for water storage.

3. Uinta Basin.--This area is the principal area of ground-water inflow to the mainstem canyons in Utah, and may well be the largest contributor of ground water in the entire upper Colorado River basin. The quantitative determination of this contribution is possible with adequate hydrologic data, and this quantity can be checked against the gain in stream flow and computed evapotranspiration losses in the basin.

Essential items of study include a groundwater study of the basin sediments to show the stratigraphy, structure, and permeability of aquifers; hydrologic studies to show the positions and fluctuations of the water table and other piezometric surfaces, and the hydraulic gradients and rates of movement of ground water; mapping of the areas of ground-water discharge, and the species of plants involved; establishment of additional gaging stations to determine the seepage from streams into the sediments of the basin. Adequate topographic maps will be needed for this study and also for planning the potential water development. The network of precipitation stations should be increased to provide sufficient information as to the areal distribution of precipitation to permit computation of the total precipitation over the basin. This study would be of special value to the State of Utah, because it would determine some major contributions to the stream that are not now measured, and because it would show the quantity of natural loss under virgin conditions. The water lost by evapotranspiration could instead be put to beneficial use without being charged to the State under the terms of the Upper Basin Compact, inasmuch as it does not contribute to the flow at Lee Ferry.

GAINS AND LOSSES IN STREAM FLOW

Principal causes of fluctuations in stream flow

At each gaging station in the Green River basin--as in other areas--the records show that the discharge of the stream is continually changing. These fluctuations result from the changing hydrologic conditions in the drainage basin above the gaging station: precipitation and melting of snow, increased inflow of tributaries or of ground water, or cessation of diversions may tend to increase the discharge of the stream; on the other hand, reduction of ground-water inflow or increased ground-water outflow, evapotranspiration, and diversions from the stream will tend to reduce the discharge. Although the stream discharge at any time is controlled by many factors, it is possible to select certain periods when the operation of certain of these factors is dominant, and thus to analyze the effect of individual factors upon stream discharge. During the early autumn, when the Green River and its tributaries are ordinarily at minimum stages for the year, it is possible to discriminate the effects of precipitation, evapotranspiration, and diversions for irrigation.

Precipitation

Intense or long-continued rainstorms produce storm runoff, which can readily be identified in the hydrographs for all gaging stations in the Green River basin. The prime objectives of the reconnaissance trips on that river have been to determine the effects upon stream flow of factors other than precipitation, and storms over the drainage basin may cause such marked changes in flow that no analysis can be made of these other factors. Thus, heavy storms during the reconnaissance trip in the first week of October 1946 caused a 60 percent increase in the discharge of the Green River at Greenriver; and storms during the 1947 reconnaissance caused marked fluctuations in tributary inflow, although the effect upon the main stream was less than during the earlier trip. The effects of precipitation were least, and conditions therefore most favorable to the discrimination of evapotranspiration losses and ground-water gains or losses, during the reconnaissance of September 1948.

Meterological conditions

Two storm periods occurred in the Green River basin during September 1948 (see fig. 2). Precipitation was reported at every Weather Bureau station during the first of these periods, September 16-19, but it amounted to less than 0.25 in. over most of the basin. At higher altitudes, however, several stations reported more than half an inch of rainfall, and the maximum recorded was 0.94 in. near the northern tip of the basin. The storm of September 25-30 was limited mainly to the southern (Utah-Colorado) half of the basin. Here also the rainfall was generally less than 0.25 in., but it was considerably greater in the headwaters of the Yampa, where the reported maximum was 1.61 in. These storm periods followed several weeks of hot, dry weather, when soils became very deficient in moisture. Characteristically in this region storms of small magnitude serve only to "lay the dust," and all the moisture is evaporated or transpired from the soil zone, without making any contribution to streams or to ground-water reservoirs.

Storm runoff

Hydrographs of stream discharge at the base gaging stations along the Green River show that storm runoff in September 1948 was of small magnitude. The hydrographs of figure 3 cover a 10-week period in 1948, during which

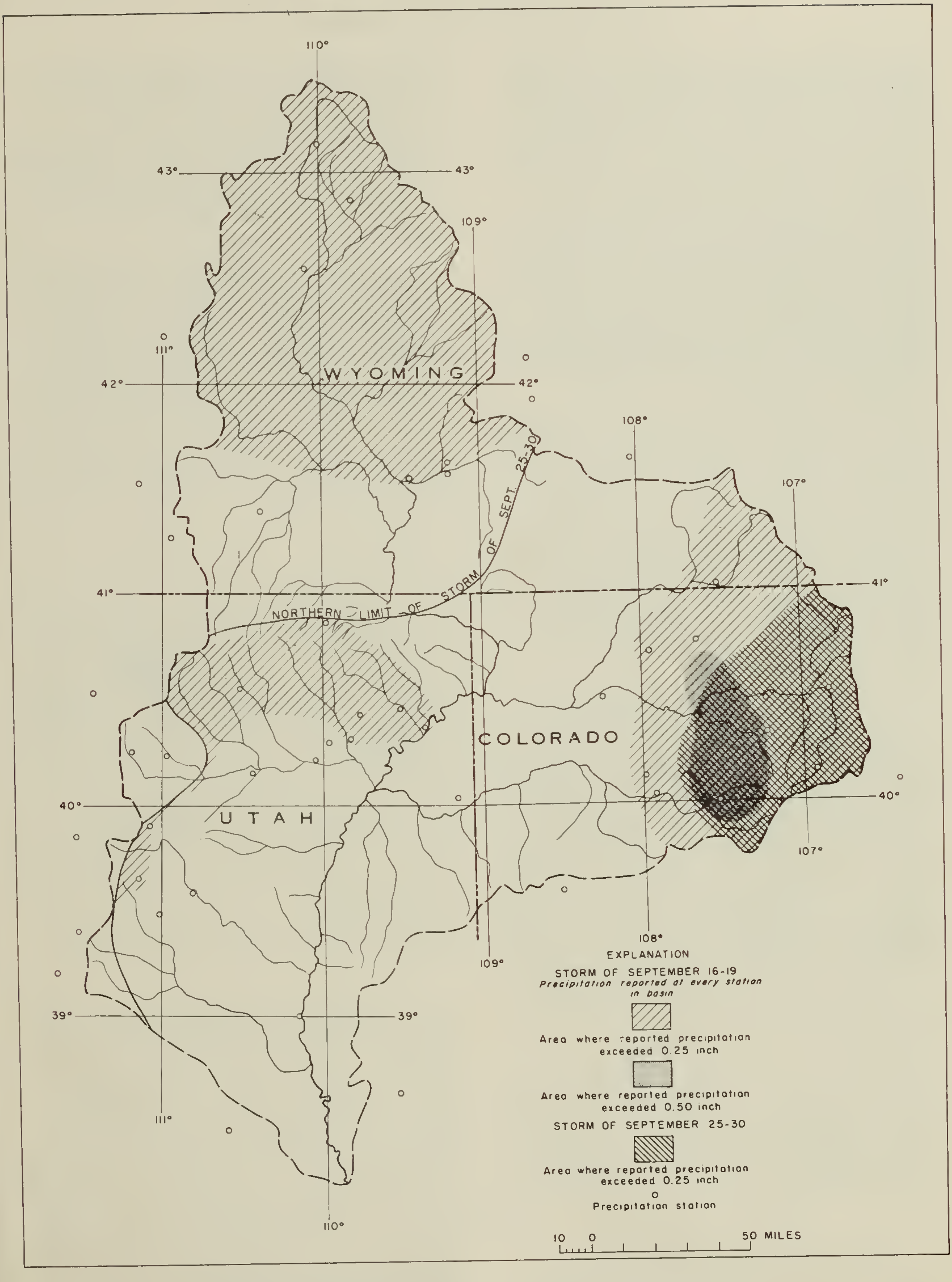

Figure 2.--Storms in Green River basin in September 1948.

five storms occurred in the Green River basin. Storm runoff is clearly indicated in the discharge at the gaging stations within the area of heaviest precipitation. Thus, in both storms in August the greatest precipitation was recorded at stations in Utah south of the Uinta Range. The stream flow at Ouray and at Greenriver increased markedly. No concurrent increase was recorded at upstream gaging stations, but there are indications of storm runoff which continued several days after the storms had ceased, and which probably originated in the headwater areas. During the period shown by the hydrographs the average velocity of the streams appears to have been such that the travel time was about 2 days between Linwood and Jensen, 2 days between Jensen and Ouray, and 3 days between Ouray and Greenriver. In many instances storm runoff peaks passing Linwood can be traced downstream and they appear on the Greenriver hydrograph a week later.

It has already been noted that during the storm of September 16-19 the greatest precipitation occurred in the northern part of the basin, in the headwaters of the Green River. The resulting storm runoff appeared at Linwood beginning September 22, 3 days after rainfall had ceased, and at Jensen 2 days later. The high areas surrounding the Uinta Basin, however, also received sufficient precipitation to cause storm runoff past Jensen and Ouray as early as September 19. The storm of September 25-30, which missed the northern part of the basin, caused no storm runoff at Linwood and Jensen, but resulted in slightly increased flow at Ouray and later at Greenriver.

The shaded areas on figure 3 represent the increased runoff that is presumed to have resulted from precipitation during the period. The lower limit of these shaded areas forms the deduced base-flow hydrograph of the river. The storm runoff probably is derived in part from precipitation directly on the channel and in part from overland flow in areas where bare and impervious rocks crop out adjacent to the channel of the river or of perennial tributaries. Channel interception may account for a major proportion of the storm flow, as in the case of the storm of August 18-23 near Jensen. The increased flow at the gaging station was marked by a rise of about 1 in. in river stage, coincident with rainfall in the vicinity amounting to about 0.9 in. Generally, however, channel interception accounts for a very minor proportion of the storm runoff. The areas where overland flow from bare rocks may reach the stream also constitute a very small proportion of the entire area of the drainage basin, but such areas may make some contributions, particularly in the canyon sections of the river. The storm flow measured at Greenriver may include appreciable quantities derived from overland flow. Other factors that undoubtedly result in increased runoff coincident with storms are the cessation of evapotranspiration draft and possibly some decrease in diversions for irrigation during storm periods.

Evapotranspiration

Evapotranspiration losses include the water evaporated directly from the water surface of the river, and the ground water discharged by evaporation from soil and marshes and by transpiration of riparian vegetation and phreatophytes (plants dependent upon ground water) along the flood plains adjacent to the river. Losses by evapotranspiration are of sufficient magnitude to cause appreciable effects on the discharge of Green River, as shown by the records from base gaging stations. These effects have been discriminated in the records covering the months of August and September 1948, as described below.

Meteorological conditions

In general throughout the Green River basin high temperatures were recorded on August 3 and 18 and September 1. Cooler weather was general August 6-11 and 22-26, when the lowest mean temperatures for the month were recorded throughout the basin. After the first five hot days in September, the mean temperatures decreased until the 8th of the month, and then increased slightly until midmonth; the days then became progressively cooler until the 20th, and changed relatively little thereafter until the end of the month. The three evaporation stations within the basin recorded the greatest evaporation losses during and immediately following the hottest days.

Diurnal effect of evapotranspiration upon river stage

The continuous records of stage at the four gaging stations along the Green River in Utah show some diurnal fluctuations which can be correlated with the changes in rate of evapotranspiration from day to night. During the period of the boat trip the storms of September 16-19 and 25-30 contributed enough water to the river or lowered the evapotranspiration rate sufficiently that these diurnal fluctuations were masked, even though there was no marked increase in stream flow. However, during the first 15 days of September the stream was not affected by storm flow, and diurnal fluctuations in stage are clearly shown. In figure 4 the gage-height graph taken from charts that have a vertical scale ratio of 1:6 have been redrawn to natural scale. The shaded areas on the graphs represent the minimum effect of evapotranspiration upon the flow of the stream at each of the gaging stations, for the fluctuations in stage record only the differences between the maximum and minimum daily evapotranspiration draft.

The gaging station near Ouray is near the center of the river's course across the Uinta Basin, a meandering 130-mile course bordered by broad flood plains covered with dense vegetation. The diurnal fluctuations in stage evidently reflect closely the evapotranspiration draft in the vicinity of the gaging station, because the stage is highest between 6 a.m. and 10 a.m., declines appreciably during the following 10 or 12 hours, and then rises (or, on a falling stage, declines at a reduced rate) until the maximum is reached the following morning. The difference between the actual stage and the straight-line trend between successive daily maxima may be as much as 0.02 ft, corresponding to a reduction of about 18 cfs in the discharge of the stream. The graph from the station at Greenriver shows a corresponding diurnal fluctuation due to evapotranspiration in Gunnison Valley, the time of maximum corresponding to that near

Ouray. Sharp fluctuations in this graph result from changes in the quantity of water diverted for irrigation.

The diurnal fluctuations in stage at the gaging station near Linwood are as great as those near Ouray, but because of the smaller stream they represent a fluctuation in discharge of not more than 12 cfs. The river is lined by phreatophytes for many miles above the gaging station, and the principal evapotranspiration draft evidently occurs well above the station, because the daily maximum river stages occur in the late afternoon and sometimes as late as 10 p.m., several hours after the maximum evapotranspiration, and the stage thereafter begins to decline in response to the evapotranspiration draft. Even greater travel time is apparently involved in fluctuations recorded at the gaging station near Jensen, which is 60 miles downstream from Browns Park, the nearest area of large evapotranspiration losses. As a result the diurnal maximum may occur as early as 6 a.m., and the decline thereafter is probably to be correlated with the evapotranspiration draft of the preceding day in Browns Park.

Effect of evapotranspiration upon stream discharge

On the hydrographs of figure 3 shading has been used to indicate the storm flow as distinguished from the base flow which is derived from ground water. The base-flow hydrographs for each gaging station show a general and fairly regular decrease in stream discharge throughout August and most of September 1948, and on the logarithmic scale used for the graphs these hydrographs approach a straight line. In detail, however, there are appreciable deviations from a straight line, and these deviations appear to result

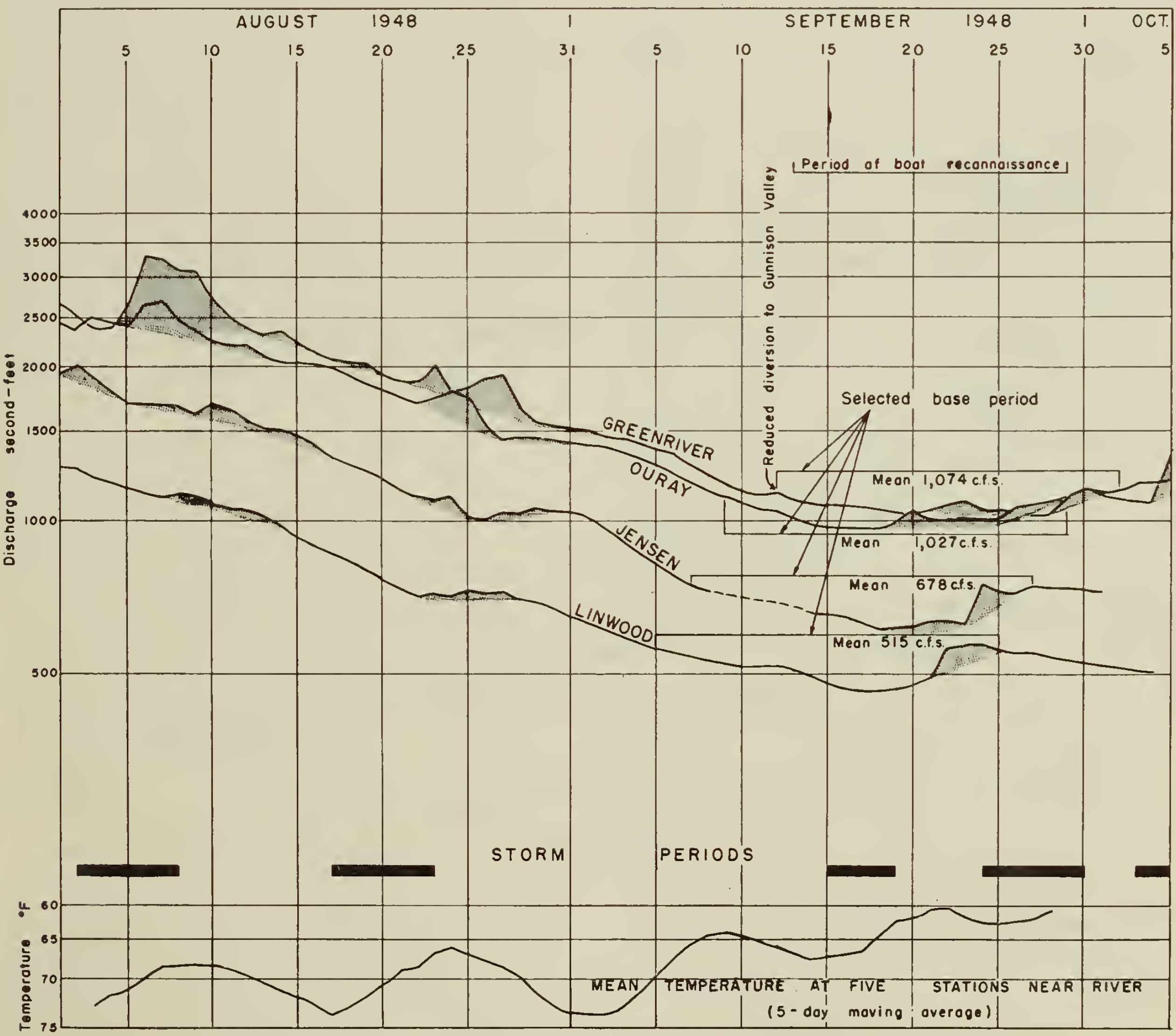

Figure 3.--Stream discharge at gaging stations on Green River, and related meterologic data, August-October 1948.

from variation in evapotranspiration losses from the river.

Correlation between stream discharge and evapotranspiration losses is evident during the first two weeks in September, when there was no precipitation anywhere in the basin, and no indication of residual storm flow from the rainfall of August 22-23. For this period the hydrographs have the steepest downward trend--that is, the rate of decrease in discharge is greatest--August 30-September 5 at Linwood, September 1-7 at Jensen, September 4-8 at Ouray, and September 6-10 at Greenriver. This sharp reduction in discharge is attributed to increased evapotranspiration resulting from the rise in temperature that began August 27 and culminated in the hot days of September 1-4. At each gaging station the rate of decline in discharge is less in the following week, which is attributed to reduced evapotranspiration during the cooler days of September 5-11. The gradually rising temperatures of September 10-15 are reflected in accelerated decline in stream flow at the gaging stations until the appearance of storm flow resulting from the precipitation of September 16-19.

Throughout the period represented by figure 3, some correlation is evident between the base-flow hydrographs and the smoothed temperature curve, which has been inverted for greater ease of comparison, inasmuch as high temperature increases the evapotranspiration and thus reduces the stream discharge. The temperature curve at the bottom of the figure is the 5-day moving average of the daily mean temperatures at the Weather Bureau stations at Green River, Wyoming, and at Jensen, Fort Duchesne, Price, and Greenriver in Utah. The hot weather, which reached peaks on August

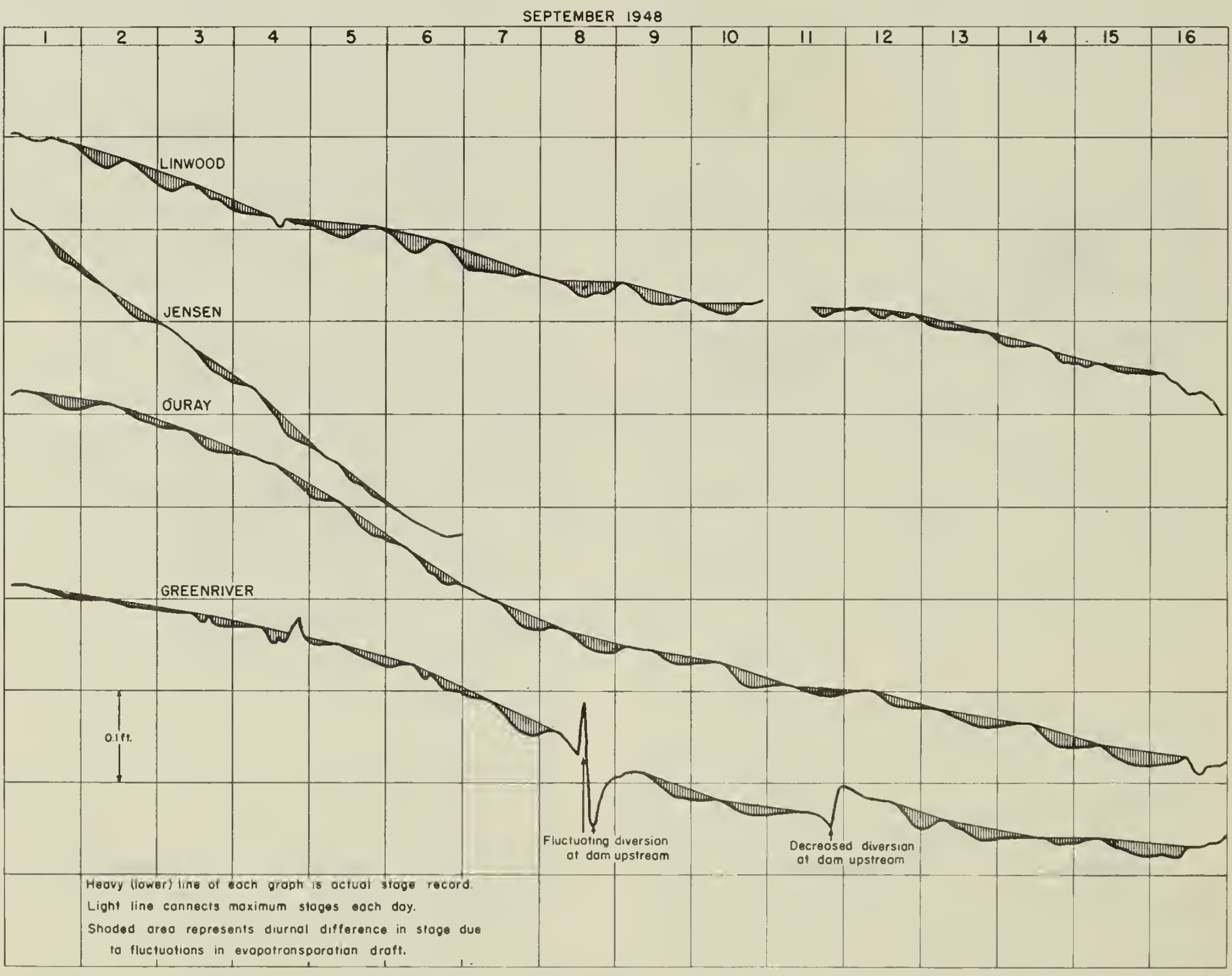

Figure 4.--Fluctuations in stage at gaging stations on the Green River.

17 and September 1 and 15, is reflected in troughs in the base-flow hydrographs for each gaging station with a lag that probably represents time of stream travel from the principal areas of evaporation. Cool periods of August 10 and 24 and September 9 have caused corresponding humps on the base-flow hydrograph due to the lower rates of evapotranspiration.

The general increase of stream discharge in late September and October may be due in small part to the decreasing rate of evapotranspiration in the fall. A large part of this rise, however, probably results from increased flow of tributaries as diversions for irrigation cease.

Diversions for irrigation

Small quantities of water are diverted from the main stem of the Green River in Utah and Colorado for irrigation of adjacent flood plains. The largest of these diversions is at mile 125.7 in Gunnison Valley, where diversions into the Wilson and Gravity canals may be as much as 80 cfs during the irrigation season. Changes in rate of diversion to these canals cause minor fluctuations in the stage at the gaging station at Greenriver, as shown in figure 4. There are also a low diversion dam in Browns Park and several pumps in the Uinta Basin that take water from the river. The quantities of water diverted have not been measured for this report, nor have the irrigated areas been determined. Instead, the irrigated areas have been included in the total area of evapotranspiration losses, and the diversions presumably would be included among the natural losses from the stream. The estimated quantities of water lost by the stream include the net losses by diversion to the irrigated flood-plain tracts.

The principal diversions for irrigation in the Green River basin are from the main stream near the headwater areas in Wyoming, and from tributaries, especially the Duchesne, Yampa, White, Black Fork, San Rafael, and Price Rivers. During the summer, all the base flow from many of the tributary channels is diverted for irrigation, and the water contributed to the Green River in that season by those tributaries consists almost entirely of return flow from the irrigation and of storm flow from occasional summer rainfall. Late in September the irrigation season draws to a close, diversions from the tributaries diminish, and the tributary inflow to the Green River increases. The increasing flow in the Green River beginning in late September (fig. 3) is attributed to this augmented tributary inflow.

Ground-water inflow

It is clearly shown on figure 3 that precipitation is a very minor source of the water in the Green River during the summer and autumn. For weeks at a time the entire flow of the stream is derived from ground-water. Thus, water from precipitation that occurred weeks or even years earlier has entered permeable rock materials beneath the land surface and then moved laterally and downward until intercepted by the channel of the main stream or some tributary, where it reappears at the surface in springs or seeps and joins the stream. For a stream that is dependent entirely upon ground-water inflow, the hydrograph (showing the relation of time to the logarithm of the discharge) tends to approach a straight line.

Quantitative estimates of stream gains and losses in September 1948

Selection of base period

On each reconnaissance trip on the Green River it has been the practice to measure the discharge of the main stream at the mouth, and at sections respectively 181, 343, and 385 miles above the mouth. These sections, together with the four base gaging stations, which are located respectively 117, 240, 314, and 437 miles above the mouth, constitute the basis for divisions of the main stem into seven segments ranging in length from 29 to 117 miles, the average length being about 60 miles. The inflow of all tributaries was also determined during these reconnaissance trips.

Preliminary calculations were made after each reconnaissance, based upon the measured discharge at both ends of each segment and the total inflow within the segment, which show "apparent" gains or losses in each segment. These apparent gains or losses include, of course, the changes resulting from ground-water inflow or outflow, evapotranspiration, and diversions from the stream. These latter changes have been of sufficient magnitude that it has not been possible to reach any conclusions directly from the reconnaissance data as to the quantities involved in ground-water inflow or evapotranspiration. Apparent losses were recorded in the segment between Linwood and Browns Park and apparent gains were recorded in the portion of the Uinta Basin below Ouray, during each trip, but these losses or gains had no clear relation to the stage of the stream. In other segments the reconnaissance data indicated apparent losses in one year and apparent gains in another, and it is obvious that changes due to ground water or evapotranspiration cannot be discriminated until the effects of changing discharge and channel and bank storage can be evaluated or eliminated.

The Green River reached its minimum stage in 1948 during the period of the boat reconnaissance in September. Quantitative estimates of the gains or losses due to ground water or evapotranspiration can be made for this period of minimum flow, provided that channel and bank storage at the beginning and end of the designated period are approximately equivalent. The period selected for analysis is therefore one in which the river stage at the beginning and at the end is approximately the same and is not subject to rapid change. The selected period progresses downstream with the approximate velocity of the river, and is thus about a week later at Greenriver than at Linwood. The selected 21-day base period is indicated on the hydrographs of figure 3.

Base period for study of gains and losses to Green River, 1948

Gaging station	Beginning of period Date	Gage height	End of period Date	Gage height	Average discharge (cfs)
Linwood	Sept. 5	1.60	Sept.25	1.59	515
Jensen	Sept. 7	.15	Sept.27	.14	678
Ouray	Sept. 9	3.64	Sept.29	3.55	1,027
Greenriver	Sept.12	5.40	Oct. 2	5.38	1,074

Gains by tributary inflow

Measured inflow

The following table shows the inflow as measured at the mouths of tributary canyons during reconnaissance of 1946, 1947, and 1948.

Observed inflow to the Green River

Stream	Mileage from mouth of Green River	Area of drainage basin (sq mi)	Discharge (cfs) Date (1946)	Discharge	Date (1947)	Discharge	Date (1948)	Discharge
Lucerne Valley:								
Henrys Fork	435.8	530	Sept.21	24.7	Sept.10	54.8	Sept.14	2.9
Flaming Gorge, Horse-shoe and Kingfisher Canyons:								
Sheep Creek	426.5	46	- do -	9.0	- do -			
Red Canyon:								
Carter Creek	422.2	105	Sept.22	22.3	- do -	38.7	- do -	19.8
Carter Creek seepage								.2
Eagle Creek	421.2	13	- do -	.8	- do -	1.0	- do -	.8
Skull Creek	416.2	5	- do -	.9	- do -	.9	- do -	1.5
Trail Creek	412.2	4	- do -	.5	- do -	.6	- do -	.9
Allen Creek	412.0	7		.5	- do -	.6	Sept.15	.5
Dutch John Draw	408.3	13			Sept.11	.1	- do -	.0
Cart Creek	407.9	41	Sept.23	1.3	- do -	3.6	- do -	1.3
Cart Creek seepage							- do -	.2
Pipe Creek	405.8	6	- do -	.2	- do -	.6	- do -	.3
					- do -	.1	- do -	.0
Gorge Creek	400.2	9	- do -	.2	- do -	.4	- do -	.1
Little Davenport Creek	399.4	8	- do -	.5	- do -	.3	- do -	.2
Jackson Creek	397.7	16			- do -	.1		
Red Creek	396.2		- do -	.1	- do -	1.4	- do -	.2
Browns Park:								
Willow Creek	380.4		Sept.24	.2	Sept.12	1.4	Sept.16	.2
Beaver Creek	377.6		- do -	.2	- do -	.5	- do -	.2
Vermilion Creek	363.5		- do -	.1	Sept.13	.1	Sept.17	.0
Lodore Canyon:								
Pot Creek	352.5		- do -	.0	- do -	1.7	- do -	.0
Echo Park:								
Yampa River	342.5		Sept.26	150	Sept.14	653	Sept.18	93.5
Pool Creek	341.7	15	- do -	0	- do -	.5	- do -	0
Mitten fault Spring	340.1		- do -	.5	- do -	1.2	- do -	1.3
Whirlpool Canyon:								
Wild Canyon seepage	393.3						- do -	.2
Jones Hole Creek	336.0		Sept.25	31.6	Sept.15	34.4	- do -	30.1
Unnamed springs	335.8				- do -		- do -	1.0
Sage Creek	334.5		Sept.27	.2	- do -	.1	Sept.10	.2
Split Mountain Canyon:								
Warm Springs	319.4						- do -	6.0
Uinta Basin above Ouray:								
Cub Creek	314.9				- do -	.1	- do -	.1
Brush Creek	302.1	255	- do -	.3	Sept.16	2.0	Sept.20	.7
Ashley Creek	296.6				- do -	12.3	- do -	3.4
Duchesne River	245.4		Sept.30	52.1	Sept.17	202	Sept.22	21.5
White River	243.6		- do -	299	Sept.18	407	- do -	340
Uinta Basin below Ouray:								
Willow Creek	237.5		- do -	3.9	- do -	.1	- do -	0
Minnie Maud Creek	210.9		Oct. 1	3.1	- do -	14.0	Sept.23	11.6

Observed inflow to the Green River--Continued

Stream	Mileage from mouth of Green River	Area of drainage basin (sq mi)	Discharge (cfs)					
			Date (1946)	dis-charge	Date (1947)	dis-charge	Date (1948)	dis-charge
Desolation Canyon:								
Jack Creek spring	187.2						Sept.23	0.1
Spring	186.1						Sept.24	.1
Flat Canyon Creek	180.3		Oct. 2	1.0			- do -	.2
Rock Creek	171.3		- do -	3.0	Sept.19	5.5	- do -	5.3
Springs on Rock Creek fan	171.1						- do -	1.2
Three Canyon Creek	167.0						Sept.25	.1
Spring	166.6						- do -	1.0
Chandler Creek	164.3		Oct. 3	.5	- do -	1.0	- do -	0
Camel Rock Spring	163.4		- do -	.5	- do -	.2	- do -	.5
MacPherson Springs	156.7		- do -				- do -	.2
Florence Creek	156.0		Oct. 4	1.5	Sept.20	.9	- do -	1.3
Gray Canyon:								
Range Creek	148.9		- do -	3.3	- do -	1.0	- do -	1.0
Coal Creek	143.5		- do -	.6	- do -	.2	Sept.26	.2
Rattlesnake Creek	139.5		- do -	.3	- do -	.7	- do -	0
Price River	135.5		Oct. 5	53.1	- do -	34.3	- do -	5.2
Gunnison Valley above Greenriver:								
Gravity Canal							Sept.28	34.3
Wilson Canal							- do -	21.6
Saleratus Wash	117.1		Oct. 7	.6	Sept.21	.1	- do -	6.3
Browns Wash	116.8		- do -	1.5	- do -	.1	Sept.27	.1
Labyrinth Canyon:								
Crystal Geyser	113.0		Oct. 8	.5			- do -	.5
Unnamed wash			- do -	.1				
San Rafael River	94.9		- do -	138			Sept.29	0

Adjusted mean flow in base period

The records from the four gaging stations along the Green River are adequate for the computation of average discharge during the selected base periods. To define within closer limits the gains and losses in the river, however, it is desirable to derive estimates of the mean flow during those periods at the other sections where measurements were made during the 1948 reconnaissance. The method used to make these estimates involves comparison of the measured discharge at the section with the recorded discharge at gaging stations both upstream and downstream, allowing for time of travel of the water. The difference in discharge is assumed to have been approximately constant during the selected period, and the estimated average discharge at the section is obtained by adding this difference algebraically to the computed average discharge at the nearest gaging station. For instance, on September 24, 1948, the discharge of the Green River at mile 181 near Flat Canyon was determined to be 1,080 cfs. This was 80 cfs more than was discharging 40 hours earlier at the gaging station at Ouray. Inasmuch as the average discharge at Ouray in the base period is computed to have been 1,027 cfs, the average for the equivalent period at Flat Canyon is estimated to have been 1,107 cfs. As a check, the discharge at Flat Canyon was 30 cfs more than that recorded at the gaging station at Greenriver 27 hours later. Adding this 30 cfs to the mean discharge at Greenriver for the period would give 1,104 cfs as the mean discharge at Flat Canyon.

Stream velocities are an important factor in the estimation of average discharge at these sections. Preliminary estimates of average velocities based on discharge measurements during the reconnaissance ranged from 1.7 mph between Linwood and the mouth of the Yampa River, to 0.9 mph below Greenriver. However, none of these measurements was made in the rapid-flowing canyon sections of the river. Analysis of hydrographs for the base gaging stations and of stream gradients indicates that the average stream velocity is approximately 2.5 mph throughout the Uinta Range (Linwood to Jensen), 1.5 mph in the Uinta Basin (Jensen to Flat Canyon), 2.4 mph in Desolation and Gray Canyons (Flat Canyon to Greenriver), and $1\frac{1}{4}$ mph below Greenriver.

The following table shows the average discharge at eight sections along the river:

Average discharge of Green River during base period

Gaging section (base stations underlined)	Miles above mouth	Date	Discharge (cfs)	Average discharge in base period (cfs)	Gain (+) or loss (-) in segment (cfs)
Linwood	437			515	+10
Taylor ranch	385	Sept.16, 1948	483	a 525	-7
Above Yampa	343	Sept.18, 1948	466	a 518	+160
Jensen	314			678	+349
Ouray	240			1,027	+78
Flat Canyon	181	Sept.24, 1948	1,080	a 1,105	-31
Greenriver	117			1,074	-100
Mouth	0	Sept.29, 1948	948	a 974	

a Estimated.

The average tributary inflow has been estimated as follows: For streams whose gaging stations are near the mouth, the average discharge has been computed for the time in which the tributary was contributing to the river during the base period. For streams whose gaging stations are some distance from the mouth, the average discharge at the gaging station in the base period has been computed and adjusted by the difference between the measured discharge at the mouth and the recorded discharge of the "same water" at the gaging station. For ungaged tributaries, measurements made at the mouth during the reconnaissance have been adjusted proportionately to the adjustments required for similar measurements on nearby gaged tributaries.

Adjusted inflow in segments of the Green River during base period, 1948

Main-stem segment	Miles above mouth	Adjusted inflow (cfs)	Gains (+) or loss (-) in segment (cfs) a	Net gain (+) or loss (-) ascribed to ground water and evapotranspiration (cfs)
Linwood-Taylor ranch	437-385	37	+10	-27
Taylor ranch-Yampa	385-343	1	-7	-8
Yampa-Jensen	343-314	146	+160	+14
Jensen-Ouray	314-240	352	+349	-3
Ouray-Flat Canyon	240-181	12	+78	+66
Flat Canyon-Greenriver	181-117	b 25	-31	-56
Greenriver-mouth	117-0	1	-100	-101

a From table at top of page.
b Does not include diversion of 56 cfs to Wilson and Gravity Canals. This diversion is accounted for in losses ascribed to evapotranspiration.

Gains from Precipitation

The proportion of stream flow at base gaging stations that is inferred to have resulted from storms is shown by shading on the graphs of figure 3. This storm flow is equivalent to an average during the 21-day base period of 8 cfs at Linwood, 12 cfs at Jensen, 25 cfs at Ouray, and 35 cfs at Greenriver. Thus, during the base period the inferred storm runoff was about $1\frac{1}{2}$ percent of the total flow at Linwood and increased to 3 percent of the total flow at Greenriver.

This storm flow, which is attributed to precipitation, is small. Thus, precipitation of 0.25 in. upon the Green River water surface alone below the Wyoming State line would increase the quantity in the stream by about 400 acre-ft. This quantity is equivalent to a continuous discharge of 10 cfs in the 21-day base period; a large part of the increased flow attributed to precipitation may be due to channel interception along the main stream. The remainder may readily be accounted for by similar interception along tributaries and by indirect effects such as the reduction of evapotranspiration draft during storms. The amounts are well within the limits of error of the estimates of tributary inflow or of evapotranspiration losses, and are ignored in the analysis of stream gains and losses.

Losses by evapotranspiration

Evapotranspiration losses include the water evaporated directly from the surface of the river and the ground water discharged by evaporation from soil and marshes or by transpiration of riparian vegetation and phreatophytes along the flood plains adjacent to the river. A large proportion of the water lost by evapotranspiration may be derived from tributaries and from ground water moving in the alluvium toward the river. Particularly in the Uinta Basin, it is likely that the water so lost comes chiefly from the basin area rather than from the main stem of the river. Nevertheless, the total draft of evapotranspiration in the channel and flood plain of the river represents a depletion from the river of water that would otherwise continue downstream.

Areas in which evapotranspiration losses occur

The areas of water surface and of flood plains along the Green River have been determined from the topographic maps, at a scale of 1:31,680, prepared during river surveys in 1904, 1914, and 1922. As a check, the areas covered by vegetation within each physiographic subdivision have been delineated on the semicontrolled aerial mosaics, at a scale of 1:63,360, prepared by the Soil

Conservation Service, and the total areas of valley floor have been determined by planimeter.

During September 1948 the discharge of the Green River was less than in the corresponding months of 1904, 1914, and 1922, and the river level was undoubtedly lower than at the time of the surveys. The width of the river during the reconnaissance is arbitrarily assumed to have been 10 percent less in the canyons and 20 percent less in other reaches than that shown on the river-survey maps. As shown in the accompanying table, the total water surface of the Green River in Utah and Colorado is computed to have been about 19,000 acres in September 1948.

The total valley area in Utah and Colorado, as determined from the topographic maps, is about 60,000 acres. This is slightly less than the total of water-surface area plus flood-plain area (63,000 acres) as determined from aerial mosaics. The difference may result from inaccuracies in maps or planimetry, or it may represent talus slopes or river bed uncovered at low water.

Areas of evapotranspiration along the Green River in September, 1948

Physiographic division	Length of channel (miles)	Average width of water surface (ft)	Area of water surface (acres)	Area of flood plain (acres)	Total area of evapotranspiration (acres)
Lucerne Valley	3.3	290	120	580	700
Horseshoe-Kingfisher Canyon	10.5	230	290	260	550
Red Canyon	29.4	170	610	240	850
Browns Park	32.6	380	1,500	6,700	8,200
Lodore Canyon	16.7	170	350	150	500
Echo Park	3.5	180	80	220	300
Whirlpool Canyon	8.6	170	190	110	300
Island Park	7.2	280	250	950	1,200
Split Mountain Canyon	7.3	160	140	60	200
Uinta Basin above Ouray	77.8	380	3,600	15,400	19,000
Uinta Basin below Ouray	52.0	420	2,700	5,300	8,000
Desolation Canyon	31.2	280	1,060	1,340	2,400
Gray Canyon	26.6	220	710	990	1,700
Gunnison Valley	34.5	390	1,640	6,360	8,000
Labyrinth Canyon	59.9	510	3,720	1,480	5,200
Stillwater Canyon	35.0	510	2,170	530	2,700
Total			19,130	40,670	59,800

Rates of evaporation from water surface

The rates of evaporation from water surfaces have been estimated from records of U. S. Weather Bureau evaporation stations in the Green River basin. For the part of the river below the Uinta Basin, the record of evaporation at Greenriver, Utah, has been taken as representative. For the Uinta Basin and the Uinta Range farther north, the records of evaporation at Fort Duchesne and Vernal, both within the Uinta Basin, have been used in computations because they are at elevations comparable to the canyon bottom as far upstream as Lodore Canyon.

It has been determined by several investigators (Sleight, 1917 and Rohwer, 1931), that the evaporation from a Weather Bureau class A land pan is about 50 percent greater than that from a reservoir surface, and Follansbee (1934), accordingly has multiplied the land-pan evaporation by a factor of 0.69 to derive the evaporation from reservoirs. Sleight (1917, p. 227), found also that evaporation from slowly flowing water was about 7 percent greater than that from still water, but did not determine the relation of stream velocity to evaporation. There are no experimental data to show the rate of evaporation from turbulent flow such as is encountered in the rapids of the Green River. In the table shown above it is assumed that evaporation from smoothly flowing water is equivalent to 85 percent of the land-pan evaporation, and that the evaporation from turbulent water is equal to the evaporation as recorded at land pans. These factors are approximately equivalent to those used by the Bureau of Reclamation, in unpublished notes, to compute the evaporation from the river surface. No allowance has been made for the moderate to strong upstream winds which are characteristic of the canyons, and which would increase the evaporation opportunity above that of the Weather Bureau evaporation stations, where average wind velocities may be less. Thus the estimates for evaporation losses from water surfaces are believed to be conservative.

Rates of evapotranspiration from flood plains

Evapotranspiration losses are least in the canyon sections of the river, where they are limited to a narrow, discontinuous strip of riparian vegetation bordering the channel. This bordering vegetation, chiefly willow and tamarix (saltcedar), with a few cottonwoods, generally occupies a strip less than 25 ft wide, and is absent along the steeper talus slopes and bedrock walls. At the mouths of larger tributaries and in the wider parts of the canyons the riparian vegetation may have a somewhat larger stand.

In the broad lowland areas traversed by the river, where extensive flood plains have developed, evapotranspiration losses are greatest. Particularly in the Uinta Basin, Gunnison Valley and Browns Park, rapid recon-

naissance indicates that evapotranspiration losses from the flood plain must be high. Huge cottonwoods line the banks of the stream in many places, and elsewhere there are dense stands of tamarix or willow. At some distance from the river the water table is in places more shallow than near the channel, and several stagnant ponds and hundreds of acres of tules and cattails are observed. Other parts of the flood plain bear greasewood and other phreatophytes, and it is concluded that the entire area of the flood plain is generally subject to evapotranspiration losses. The total flood-plain area along the Green River, as determined from river-survey topographic maps, is about 41,000 acres.

Integration methods of estimating evapotranspiration draft involve the determination of unit values of consumptive use for each type of vegetation, multiplying these unit values by the area covered, and adding or integrating the products thus obtained to derive the total evapotranspiration draft in a designated area or valley. Along the Green River in Utah and Colorado there is a varied assemblage of phreatophytes, but the areas covered by individual species have not been mapped for any portion of the area. Furthermore, no studies have been made within the Utah portion of the basin to determine consumptive use of the various types of native vegetation. Accordingly, estimates of the consumptive use by native vegetation are derived by selecting an average unit rate for the assemblage of riparian vegetation and multiplying that rate by the area covered by phreatophytes. Three methods of estimating the rates of evapotranspiration are described and a summary table shows the rates derived by these methods (p. 27).

Correlation of consumptive use with land-pan evaporation.--The use of water by native vegetation has been the subject of intensive research in many parts of the West, and the results of many of these studies have been summarized by Young and Blaney (1942). These experiments show that the rate of evapotranspiration is closely related to the depth to the water table, and that it varies considerably for different species of plants. Detailed information as to the position of the water table under the flood plains of the Green River is lacking, but it is assumed that, when the river was at high stage early in the summer of 1948, the water table was generally within a foot or two of the surface under the flood plains, and that as the river stage declined the water table dropped under some parts of the flood plain until it was as much as 6 to 8 ft beneath the surface in September.

In many studies of the use of water by plants throughout the West, standard Weather Bureau class A evaporation pans have been operated at the sites of the experiments. The experimental data indicate that transpiration from tamarix has commonly been 125 to 150 percent of the land-pan evaporation, from willows and cottonwoods 65 to 85 percent, from cattails 130 to 190 percent, from tules 95 to 150 percent, from mixed river-bottom vegetation 60 to 70 percent, from salt grass 60 to 75 percent, from greasewood 25 to 50 percent, and from meadow grass 20 to 100 percent. The estimates of evapotranspiration as derived from records of land-pan evaporation in the table on page 28 are based upon the assumption that the rate of evapotranspiration from the mixed phreatophytes along the Green River is approximately the same as from willows and cottonwoods, and that this is about 80 percent of the rate of land-pan evaporation.

A significant development along the Green River is the rapid invasion of tamarix, which is migrating upstream to replace other phreatophytes and is now abundant in the Uinta Basin and areas farther south. Experimental data indicate that this plant consumes $1\frac{1}{2}$ to 2 times the amount of water used by willows and cottonwoods, and the gradual replacement of these species by tamarix will thus result in a change in the so-called virgin conditions, and a greater depletion of stream flow by vegetation than in the past.

Thornthwaite's "potential evapotranspiration."--Thornthwaite (1948, p. 56), in a recent article states: "The vegetation of the desert is sparse and uses little water because water is deficient. If more water were available, the vegetation would be less sparse and would use more water. There is a distinction, then, between the amount of water that actually transpires and evaporates and that which would transpire and evaporate if it were available. When water supply increases, as in a desert irrigation project evapotranspiration rises to a maximum that depends only on the climate. This we may call "potential evapotranspiration," as distinct from actual evapotranspiration." Along the bottom lands of the Green River, where the root zone is well supplied with water, it is considered that the actual evapotranspiration would approximate the potential evapotranspiration as thus defined.

From his study of available experimental data concerning evapotranspiration and consumptive use, Thornthwaite has derived a formula that permits computation of potential evapotranspiration at any place of known latitude, if temperature records are available (1948, p. 89-94). This formula is empirical and complicated, and its solution is dependent upon nomographs and tables as computing aids. Briefly, an annual heat index I is obtained from the equation $i = (t/5)^{1.514}$, in which t is the mean monthly temperature. The potential evapotranspiration, e, is determined by graphic solution of the equation

$$e = 1.6\ (10t/I)^{a}$$

$$\text{in which } a = 0.49239 + 1.7921\left(\frac{I}{100}\right) + 0.711\left(\frac{I}{100}\right)^{2} + 0.675\left(\frac{I}{100}\right)^{3}$$

This formula gives unadjusted rates of evapotranspiration, which are then multiplied by a factor that varies with the month and the latitude in order to obtain the adjusted potential evapotranspiration. The potential evapotranspiration has been computed in this manner for the month of September 1948 at four places along the Green River for which temperature records are available.

Blaney and Criddle's estimated water requirements.--Because few measurements of consumptive use have been made in the upper Colorado River basin, Blaney and Criddle (1949), have suggested a method of utilizing the results of studies in other areas to derive estimates of consumptive use in that basin. Their formula assumes that monthly consumptive use, u, varies directly in proportion to a factor f, which is obtained by multiplying the mean monthly percent of daytime hours, p; that is,

$$u = kf = k \frac{tp}{100}$$

in which k is an empirical coefficient which varies with the type of vegetation and which is based on the results of experiments in other areas. For September this coefficient has been estimated as 1.3 for the dense native Valley, and 1.1 for the medium growth north of the Uinta Range.

Rates of evapotranspiration during September, 1948

Location	Monthly evapotranspiration (in.)		
	Land-pan evaporation x 0.8	Thornthwaite's potential evapotranspiration	Blaney and Criddle's water requirements
Manila, Lucerne Valley			5.2
Vernal, Uinta Basin	4.7	3.3	6.5
Fort Duchesne, Uinta Basin	4.6	3.4	6.8
Greenriver, Gunnison Valley	6.8	4.3	7.8

Total estimated losses by evapotranspiration

The rates of evapotranspiration determined by the three methods described above range rather widely and give correspondingly wide ranges in determinations of total evapotranspiration losses from the river.

According to rough computations based on Thornthwaite's formulas the total evapotranspiration along the Green River in Utah and Colorado was at an average rate of about 340 cfs in September 1948. Along the lower 156 miles of the river, however, (between the head of Desolation Canyon and the confluence with the Colorado), the evapotranspiration by this formula would have been less than the computed losses in stream flow, even assuming that ground-water inflow was nil. It is concluded that the evapotranspiration rates as computed by this method are less than actual rates.

Using the Blaney and Criddle formula, the total evapotranspiration along the Green River in September 1948 was at a rate of nearly 500 cfs, or about 50 percent greater than that estimated on the basis of Thornthwaite's formula. When this formula is used to determine total evapotranspiration in the river segments listed on page 24, however, over-all balance within the segments can be achieved only by assuming rates of ground-water inflow that are not in accord with our present knowledge of ground-water hydrology. It appears that the evapotranspiration as computed by the Blaney-Criddle method is higher than the actual rate. For example, in the part of the river between Linwood and the Yampa River the ground-water inflow must be at an average rate of 37 cfs during the base period to sustain evapotranspiration, as computed by the Blaney-Criddle formula. Between the Yampa River and Jensen the evapotranspiration was computed from the formula to be of the same order of magnitude. Yet in that reach there are limestone aquifers which might be expected to contribute substantially to the river, and are known to discharge several cfs through springs. In short the prospects for ground-water inflow are far more favorable between the Yampa River and Jensen than between the Yampa River and Linwood.

The mean of the rates developed by the Thornthwaite and the Blaney and Criddle formulas approximates rather closely the rate derived from the land-pan evaporation multiplied by a factor of 0.8. In the computations below it is assumed that the rate of evapotranspiration during September 1948 was 4 in. in Lucerne Valley, 4.8 in. in the Uinta Basin, and 6.6 in. in Gunnison Valley. These rates correspond to mean daily rates of 0.011, 0.013, and 0.018 foot, respectively. Rates for intervening reaches of the river are interpolated from these rates. In this interpolation it has been assumed that in canyons, particularly east-west canyons, the rate decreased somewhat because of the lower average temperature and the greater amount of shade.

The accompanying summary of daily evapotranspiration losses shows that the average daily evaporation from the river exceeded 300 acre-ft in September 1948, and that the evapotranspiration loss from the valley was about 550 acre-ft per day additional. The loss from the river, equivalent to a continuous flow of 432 cfs, is nearly as great as the total observed tributary inflow in Utah and Colorado. The estimate is nevertheless believed to be conservative. It represents an average evaporation during the month of 5-3/4 in. from the river, and an evapo-

transpiration draft of 3-1/3 in. from the flood-plain areas.

Estimated average daily evapotranspiration losses along the Green River in September 1948

Physiographic division	Evaporation from water surfaces		Evapotranspiration from land surfaces		Total daily evapotranspiration	Average depletion from river
	Assumed daily rate (feet)	Daily loss in section (acre-feet)	Assumed daily rate (feet)	Daily loss in section (acre-feet)	Acre-feet	Second-feet
Lucerne Valley	0.013	1.6	0.011	6.4	8.0	4
Horseshoe-Kingfisher Canyon	.015	4.4	.010	2.6	7.0	3
Red Canyon	.015	9.2	.009	2.2	11.4	6
Browns Park	.014	21.0	.011	73.7	94.7	47
Lodore Canyon	.016	5.6	.010	1.5	7.1	4
Echo Park 8	.014	1.1	.012	2.6	3.7	2
Whirlpool Canyon	.016	3.0	.011	1.2	4.2	2
Island Park	.014	3.5	.013	12.4	15.9	8
Split Mountain Canyon	.016	2.2	.012	.7	2.9	2
Uinta Basin above Ouray	.014	50.4	.013	200.2	250.6	126
Uinta Basin below Ouray	.014	37.8	.013	68.9	106.7	54
Desolation Canyon	.017	18.0	.013	17.4	35.4	18
Gray Canyon	.017	12.1	.014	13.9	26.0	13
Gunnison Valley	.018	29.5	.018	114.5	144.0	73
Labyrinth Canyon	.018	67.0	.017	25.2	92.2	46
Stillwater Canyon	.018	39.0	.017	9.0	48.0	24
Total		305.4		552.4	857.8	432

Losses by diversion for irrigation

Minor diversions for irrigation are made by gravity in Gunnison Valley and Browns Park, and by pumping in the Uinta Basin. The diversions at the head of the Gunnison Valley totaled 56 cfs on September 27, 1948, but most of the discharge from Saleratus Wash (6 cfs) on the same day was return flow from irrigation with this diverted water, and numerous small springs and seeps observed along the river channel obviously came from the same source. The irrigated area of Gunnison Valley is assumed to have a consumptive use equivalent to the rate of evapotranspiration draft of the native phreatophytes, and the total evapotranspiration from flood plain and cultivated land in Gunnison Valley (both above and below the town of Greenriver) has been computed to be equivalent to an average flow of 73 cfs. This is considered to be a net quantity, equivalent to diversion by canals plus natural loss minus return seepage.

The diversions to other irrigated areas were not measured. Those areas have likewise been included in the total area of evapotranspiration, and the loss by diversion thus becomes a part of the evapotranspiration loss.

Estimated gains by ground-water inflow

The ground-water inflow to the Green River observed during the several reconnaissance trips is included in the tabulation on pages 22-23. The warm springs in Split Mountain Canyon yielded the largest quantities, but springs at the Mitten fault and in Desolation Canyon also discharged at the rate of a second-foot or more. The total observed ground-water inflow to the Green River was about 12 cfs.

The river cuts numerous permeable formations in its course, and in many places geologic structures encourage movement of ground water toward the river channel. As pointed out in the discussion of geology and ground-water hydrology, the Uinta Basin is a structural basin in which ground water might be expected to move toward the axis of the trough and thence into the Duchesne and White Rivers which drain the basin and ultimately join the Green River. It has been suggested that in Split Mountain Canyon the spring discharge in the bed of the river may be greater than that observed above river level. Whirlpool Canyon and Desolation Canyon are other areas where conditions are favorable for ground-water seepage into the river. In Gunnison Valley some ground-water inflow was observed and considerable seepage was inferred to occur from the lands which are irrigated by water diverted from the river.

Some idea as to the quantity of ground-water inflow may be obtained from the differences between the inflow and outflow in segments of the channel, and the estimates of other gains and losses in those segments as derived in this manner, is shown for several segments of the channel in the following table.

Estimated ground-water inflow to the Green River
September 1948

Main-stem station	Adjusted discharge[a] (cfs)	River segment	Tributary inflow b	Evapotranspiration loss[c] (cfs)	Derived ground-water inflow[d]
Green River at Linwood	515				
		Above mouth of Yampa River	38	64	29
Green River above Yampa River	518				
		Yampa River to Jensen	138	14	36
Green River at Jensen	678				
		Uinta Basin above Ouray	352	126	123
Green River at Ouray	1,027				
		Uinta Basin below Ouray	12	54	120
Green River at Flat Canyon	1,105				
		Below Uinta Basin	21	174	22
Green River at Mouth	974				
Total			561	432	330

a From table on p. 24.
b From table on p. 24, but deducting observed ground-water inflow.
c From table on p. 28.
d Evapotranspiration loss, plus gain or minus loss in adjusted flow of Green River in segment, minus tributary inflow in segment.

This table shows that the derived ground-water inflow was about 330 cfs during the period of minimum flow in 1948, when the average adjusted tributary inflow was about 560 cfs. The area of greatest contribution was the Uinta Basin, where ground-water inflow is estimated to have been at a rate of about 240 cfs.

The estimates of ground-water inflow are dependent upon those of evapotranspiration, and thus carry the accumulated errors of those estimates. The ground-water inflow could be determined independently during the winter, when evapotranspiration is at a minimum. A reconnaissance during that period would furnish valuable check data, but running the river through ice and icy water would be an extremely hazardous operation. So far no such trips have been made, even for adventure.

CHEMICAL CONSTITUENTS IN THE WATER

Chemical analyses

During September 1948 samples of the water of the Green River were collected at eight points. Samples were also collected of the waters of 24 streams, 11 springs and seeps, and the Crystal Geyser well flowing into the Green River. The chemical analyses of these samples are tabulated below, together with analyses of the samples of these waters collected at other times.

The water of the Crystal Geyser well was the most highly mineralized water sampled, and it is fortunate that its contribution to the river probably averages less than 250 gpm. The flow of several tributaries was being diverted for irrigation at the time of sampling, and the water entering the Green River from those streams was largely return flow from that irrigation. In Henrys Fork, Brush Creek, Ashley Creek, Duchesne River, and Price River, the dissolved solids ranged from 2,400 to more than 6,000 ppm. A sample from Brush Creek taken in October 1948 after irrigation diversions had decreased, contained less than half as much dissolved material.

Several streams drain areas of extensive outcrops of Cretaceous and Tertiary shales. Browns Wash and Saleratus Wash, flowing over the Mancos shale near Greenriver, carried 5,400 and 2,400 ppm respectively of dissolved solids, chiefly sodium and calcium sulfates. Other streams flowing over Cretaceous shales, including Coal Creek, Rattlesnake Creek, and Price River, also yield rather highly mineralized sulfate waters to the Green River.

Chemical analyses, in parts per million, of water from Green River

Point of sampling	Miles above mouth	Date	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Dissolved solids		Total hardness as $CaCO_3$
											Parts per million	Tons per ac. ft.	
Linwood	437	Sept.14, 1948	3.7	56	27	72	172	233	16	0.6	493	0.67	250
Above Yampa River	343	18	4.7	52	26	64	163	210	17	.5	454	.62	236
Jensen	314	21-29	5.1	54	25	82	174	207	37	.4	497	.68	236
Above Duchesne River	246	22	4.3	58	24	78	172	209	37	1.0	496	.67	243
Do - - -	246	29	4.6	60	31	74	176	234	35	.5	526	.72	277
Ouray	240	22	9.9	68	29	91	192	241	54	1.4	589	.80	288
Flat Canyon	181	24	10	66	30	93	200	238	55	1.4	592	.81	288
Greenriver	117	11-20	9	64	29	91	208	229	47	.8	573	.78	278
Do - - -	117	21-30									638	.87	
Do - - -	117	Oct. 1-10									781	1.06	
Do - - -	117	11-19	11	82	37	116	238	329	49	3.5	745	1.01	356
Mouth	0	Sept.29	8.0	65	27	106	207	255	49	.5	612	.83	273
Henrys Fork	435.8	14	11	290	182	437	264	1,800	225	16	3,090	4.20	1,470
Sheep Creek	426.5	- - do - -	11	147	48	15	176	424	9	.1	741	1.01	564
Carter Creek	422.2	- - do - -	9.7				36	8.4	.5	1.8			
Carter seeps	422.2	- - do - -	9	20	7	19	60	21	2	1	91	.12	79
Eagle Creek	421.2	- - do - -	19				109	4.9	3	1.4			
Skull Creek	416.2	- - do - -	22	44	18	10	221	21	2	.3	224	.30	184
Trail Creek	412.2	15	24	62	15	7.4	261	11	4	1.2	253	.34	216
Cart Creek	407.9	- - do - -	11				85	7.0	1.5	0			
Red Creek	396.2	- - do - -	17	94	101	320	296	798	192	1.4	1,670	2.27	650
Beaver Creek	377.6	16	60	98	31	37	356	139	11	1.3	553	.75	372
Yampa River	342.5	18	8.8	44	20	76	177	97	78	1.5	412	.56	192
Mitten Spring	340.1	- - do - -	13	74	29	237	239	94	370	3	938	1.28	304
Jones Hole Creek	336.0	19	15	44	17		197	13	2	2.6	191	.26	180
Sage Creek	334.5	- - do - -	15	143	42	4.1	189	363	4	.1	664	.90	530
Warm Springs	319.4	- - do - -	18	97	32	193	198	212	291	1	942	1.28	374
Brush Creek	302.1	30	7.4	262	136	313	378	1,450	37	27	2,420	3.29	1,210
Do - - -	302.1	Oct. 6	12	192	30	52	209	513	6	3.4	911	1.24	602
Ashley Creek	296.6	Sept.30	18	319	232	264	299	1,930	44	11	2,970	3.74	1,750
Do - - -	296.6	Oct. 6	18	328	225	197	320	1,780	32	14	2,750	3.45	1,740
Springs	?	- - do - -	24	76	35	89	342	166	46	10	614	.84	334
Duchesne River	245.4	Sept.22	8.9	156	126	513	267	1,230	370	1.5	2,540	3.45	907
Do - - -	245.4	29	13	132	99	397	277	974	254	1.2	2,010	2.73	736
White River	243.6	22	16	74	30	101	222	236	70	1.4	638	.87	308
Do - - -	243.6	29	17	76	33	94	220	240	69	1.1	638	.87	325
Minnie Maud Creek	210.9	Sept.18, 1947	26	47	69	108	444	243	13	.5	725	.99	401
Do - - -	210.9	Sept.23, 1948	25	50	78	127	467	305	15	1.3	831	1.13	446
Flat Canyon seepage	180.3	24	26	48	35	53	332	92	6	2	426	.58	264
Rock Creek	171.3	Sept.19, 1947		53	35	30	301	81	6	1	354	.48	276
Do - - -	171.3	Sept.24, 1948	27	51	33	43	310	92	4	.5	403	.55	262
Rock Creek return flow	171.1	- - do - -	22	118	31	148	206	291	192	2	905	1.23	422
Three Canyon seep	167.0	25	24	65	39	60	360	143	6	2	516	.70	322
Spring	166.6	- - do - -	27	52	39	87	417	127	4	1	543	.74	290
Chandler Creek	164.3	Sept.19, 1947		65	40	66	303	203	7	1	532	.72	326
Camelrock Spring	163.4	Sept.25, 1948	26	70	41	73	321	220	7	1	596	.81	343
Florence Creek	156.0	- - do - -	28	58	49	71	300	235	7	.2	596	.81	346
Spring	151.1	- - do - -	18	10	6	250	492	176	5	1	707	.96	48
Range Creek	148.9	Sept.20, 1947	21	48	57	124	472	207	16	.0	706	.96	354
Do - - -	148.9	Sept.25, 1948	18	39	54	132	448	209	15	.5	688	.94	320
Coal Creek	143.5	Sept.20, 1947	17	108	127	478	388	1,390	46	.0	2,360	3.21	474
Rattlesnake Creek	139.5	- - do - -	23	70	126	366	462	1,020	33	1	1,870	2.54	692
Price River	135.5	- - do - -	5	249	229	773	229	2,800	98	3	4,270	5.81	1,560
Do - - -	135.5	Sept.26, 1948	3.7	347	338	1,140	234	4,180	142	3.5	6,270	8.53	2,260
Saleratus Wash	117.1	Sept.21, 1947	14	469	124	402	200	2,210	63	1.1	3,380	4.60	1,680
Do - - -	117.1	Sept.27, 1948	13	325	83	306	181	1,530	53	1.6	2,400	3.26	1,150
Saleratus Wash	117.0	- - do - -	10	97	36	131	220	399	55	1.9	838	1.14	390
Browns Wash	116.8	- - do - -	17	516	188	914	266	3,540	102	.0	5,410	7.36	2,060
Crystal Geyser well	113.0	Sept.22, 1948	13	1,000	225	4,070	4,400	2,410	4,370		14,300	19.4	3,420

The purest water received by the Green River in Utah at minimum stage evidently comes from the tributaries that rise in the Uinta Range and enter the river above Jensen. Many of these carry less than 250 ppm of dissolved solids. Jones Hole Creek, fed by springs rising from Pennsylvanian limestones, has a calcium-bicarbonate water with about 200 ppm of dissolved matter. The Yampa River probably has a lower concentration of dissolved salts at most times than does the Green River above their junction. Thus, the water in the Green River can have a lower concentration of dissolved solids as it leaves the Uinta Range near Jensen, than it had when it entered that range at Flaming Gorge, below Linwood.

In the Uinta Basin and farther south, the tributary stream generally carried a greater proportion of dissolved materials than did the Green River in September 1948. The modrate deterioration in quality of the water downstream from the mouth of the Duchesne River, as shown in the preceding table, is due in part to this tributary inflow, and in part to ground-water inflow and to concentration resulting from evaporation and transpiration.

Gains and losses in dossolved mineral load

In the 1948 reconnaissance it was hoped that it would be possible to make an accounting of the dissolved solids carried by the stream on the basis of the analyses of the water sampled. Two major weaknesses are recognized in this chemical "accounting". First, it was not possible to "ride" the same water down the stream during the trip, and analyses of composites of daily samples collected at Greenriver show a considerable variation in quantity of dissolved solids in the stream even over short periods. Second, considerable ground-water inflow has been inferred to occur in certain reaches of the

Estimated gains and losses in dissolved mineral load, in tons per day, of the Green River
Sept. 13-17, 1948

Contributor	Adjusted discharge (second feet)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Carbonate (CO_3)	Sulfate (SO_3)	Chloride (Cl)	Nitrate (NO_3)	Total dissolved solids
Green River at Linwood, sampled Sept. 14	515	5.1	78	38	100	118	324	22	0.8	686
Henrys Fork	3	.1	2.3	1.5	3.5	1.1	15	1.8	.1	25
Sheep Creek	8	.2	3.2	1.0	.3	1.9	9.2	.2	.0	16
Tribs. in Red Canyon	25.9	.9	1.0	.3	.2	2.5	.6	.0	.0	5.5
Tribs. in Browns Park	.6	.1	.2	.1	.2	.3	.6	.1	.0	1.5
Evapotranspiration[1]	-35	-.2	-2.3	-1.1	-2.8	-3.3	-9.4	-.6	.0	-19.7
Green River above Yampa River computed from above	518	6.2	82.4	39.8	101.4	120.5	340.0	23.5	.9	714
Sampled Sept. 18		6.6	73	36	90	112	294	24	.7	635

1 Assuming that all ground water inflow in this reach was lost by flood-plain evapotranspiration, chiefly in Browns Park; that 14 cfs was lost from the river by seepage to the flood plain, thence to evapotranspiration; and that 21 cfs was evaporated from the river with no reduction in mineral load. Deductions represent 14/515 of load above mouth of Yampa River.

Contributor	Adjusted discharge (second feet)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Carbonate (CO_3)	Sulfate (SO_3)	Chloride (Cl)	Nitrate (NO_3)	Total dissolved solids
Green River above Yampa River (computed)	518	6.2	82.4	39.8	101.4	120.5	340.0	23.5	.9	714
Yampa River and underflow	112	2.7	13	6.0	23	26	29	24	.4	125
Mitten Spring	1.3	.1	.3	.1	.8	.4	.3	1.3	.0	3.3
Jones Hole Creek and seepage	41	1.7	4.9	1.9	.0	11	1.4	.2	.3	21
Sage Creek	.2	.0	.1	.0	.0	.0	.2	.0	.0	.4
Warm Springs	20	1.0	5.2	1.7	10	5.3	11	16	.0	51
Evapotranspiration[2]	-14	-.2	-1.8	-.9	-2.3	-2.8	-6.5	-1.2	.0	-15.7
Green River at Jensen computed from above	678	11.5	104.1	48.6	132.9	160.4	375.4	63.8	1.6	899
Sampled Sept. 21-29		9.3	99	46	150	157	379	68	.7	910

2 Assuming 5 cfs evaporation from river and 9 cfs seepage to flood plains in Echo Park and Island Park where water is lost by evapotranspiration; ground-water inflow is included in totals for Yampa River, Jones Hole Creek, and Warm Springs. Deductions represent 9/518 of mineral load at Jensen.

Contributor	Adjusted discharge (second feet)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Carbonate (CO_3)	Sulfate (SO_3)	Chloride (Cl)	Nitrate (NO_3)	Total dissolved solids
Green River at Jensen (computed)	678	11.5	104.1	48.6	132.9	160.4	375.4	63.8	1.6	899
Brush Creek	.7	.0	.5	.3	.6	.3	2.7	.1	.0	4.6
Ashley Creek	2.8	.1	2.4	1.8	2.0	1.1	15	.3	.1	22
Springs and seeps (one sample)[3]	18	1.2	3.7	1.7	4.3	8.2	8.1	2.2	.5	30
Duchesne River	23.5	.6	9.9	8.0	33	8.3	78	23	.1	161
White River	325	14	65	26	89	96	207	61	1.2	560
Green River at Ouray computed from above	1,027	27.4	185.6	86.4	261.8	274.3	686.2	150.4	3.5	1,677
Sampled Sept. 22		27	189	80	252	262	668	150	3.9	1,630

3 Assuming ground-water inflow in this reach met all requirements for flood-plain evapotranspiration, and also provided 18 cfs seepage to river. Evaporation from river assumed to be 21 cfs.

Contributor	Adjusted discharge (second feet)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Carbonate (CO_3)	Sulfate (SO_3)	Chloride (Cl)	Nitrate (NO_3)	Total dissolved solids
Green River at Ouray (computed)	1,027	27.4	185.6	86.4	261.8	274.3	686.2	150.4	3.5	1,677
Minnie Maud Creek	12	.8	1.6	2.5	4.1	7.5	9.9	.5	.1	26.9
Ground-water seepage[4]	85	6.0	11	8.0	12	38	21	1.4	.5	98
Green River at Flat Canyon (computed)	1,105	34.2	198.2	96.0	277.9	319.8	717.1	152.2	4.1	1,802
Sampled Sept. 24		30	197	90	277	294	710	164	4.2	1,770

4 Assuming ground-water inflow in this reach met all requirements for flood-plain evapotranspiration, and also yielded 85 cfs to river from springs and seeps; assuming also that ground-water seepage to river is similar in dissolved constituents to seepage at Flat Canyon. Evaporation from river 19 cfs.

Contributor	Adjusted discharge (second feet)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Carbonate (CO_3)	Sulfate (SO_3)	Chloride (Cl)	Nitrate (NO_3)	Total dissolved solids
Green River at Flat Canyon (computed)	1,105	34.2	198.2	96.9	277.9	319.8	717.1	152.3	4.1	1,802
Rock Creek	6.5	.5	1.1	.6	1.1	2.5	2.2	.7	.0	8.7
Springs[5]	1.6	.1	.2	.2	.3	.8	.7	.0	.0	2.4
Florence Creek	1.3	.1	.2	.2	.3	.5	.8	.0	.0	2.1
Range and Coal Creeks	1.2	.1	.2	.2	.6	.7	1.3	.1	.0	3.2
Price River	7.3	.1	6.8	6.7	22	2.3	82	2.8	.5	124
Browns and Saleratus Washes	5.6	.1	1.6	..6	2.2	1.6	6.9	.8	.0	13.5
Crystal Geyser well	.5	.0	1.4	.3	5.5	2.9	3.3	5.9	.0	19
Evapotranspiration[5]	-71	-2.3	-13.5	-6.8	-19.9	-21.2	-52.3	-10.5	-.3	-126
Green River at mouth (computed)	974	32.9	196.2	98.9	290.0	309.9	762.0	152.1	4.3	1,829
Check by analysis of sample Sept. 29		21	171	71	279	268	671	129	1.3	1,610

5 Assuming that except for the springs listed, all ground-water inflow to this reach was lost by flood-plain evapotranspiration before reaching the stream; and that evapotranspiration losses also included some seepage from stream and most of the eater diverted for irrigation. Total evapotranspiration losses in reach assumed to be 155 cfs, including 84 cfs evaporation from river. Deductions represent 71/1,105 of mineral load at mouth.

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stream, and the samples collected from springs are probably far from adequate representations of this inflow.

In the tabulation on page 31, the quantities of dissolved materials are given in tons per day. Thus they represent total weights of each constituent carried in the main stream or its tributaries. The unsampled ground-water inflow to the river has been assumed to be of a similar composition to that of springs sampled in the reach where the inflow occurred. Evaporation from the stream does not reduce the quantity of dissolved mineral constituents in the water, except that calcium carbonate may be precipitated. Where water is lost by seepage from the stream and subsequent evapotranspiration from the flood plain, it has been assumed that the mineral constituents would be reduced proportionately to the loss of water from the stream; actually, a substantial part of these salts eventually will be redissolved and will enter the stream again. Considering all the uncertainties for which assumptions had to be made, the difference between computed and analyzed load at the mouth of the river is less surprising than the very close agreement at other points where samples were taken.

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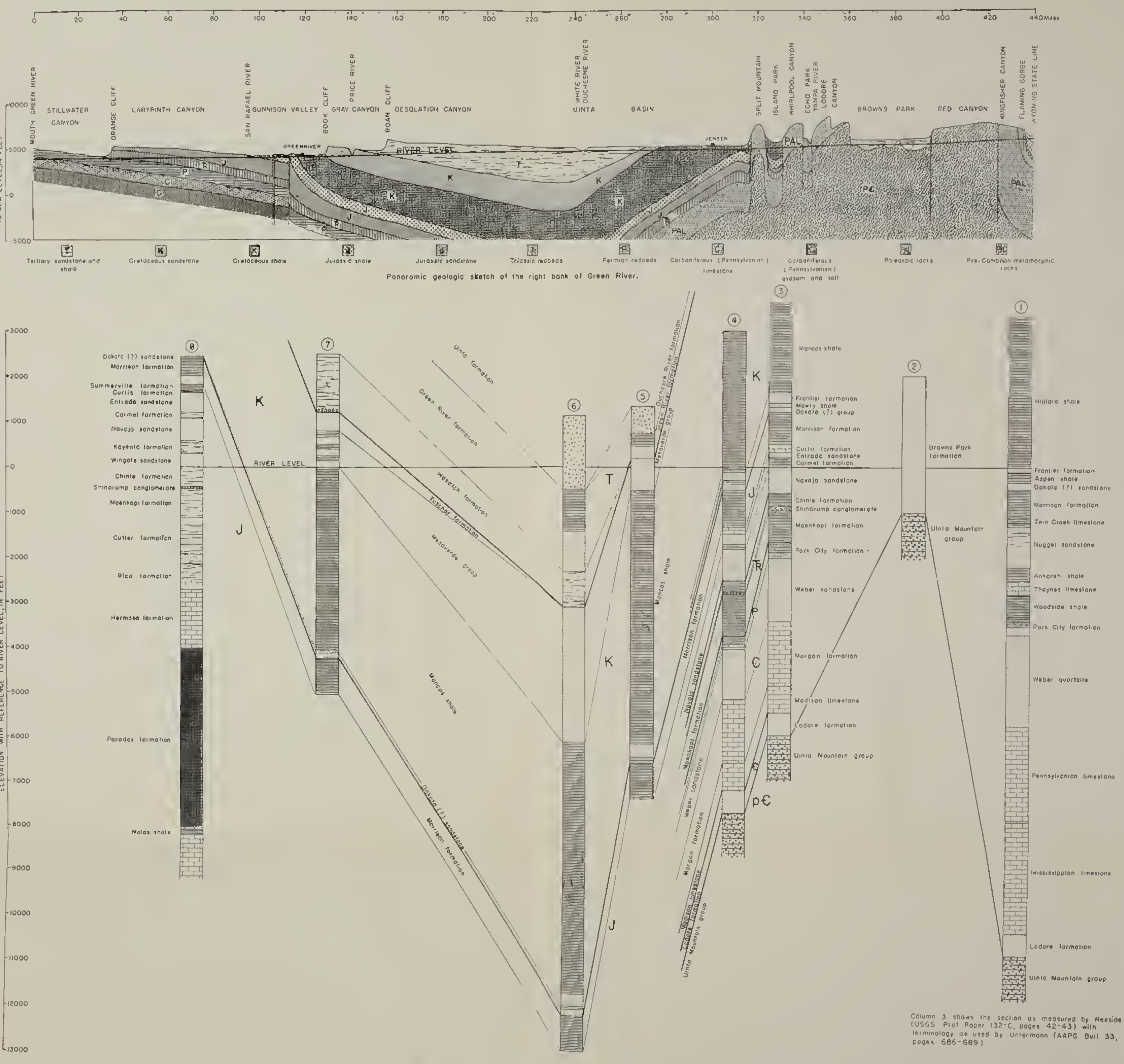

See references corresponding to numbers of stratigraphic columns on page 6

STRUCTURAL SECTION AND STRATIGRAPHIC COLUMNS ALONG THE GREEN RIVER